GPI: Modeling of AO-corrected coronagraphs

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With slides courtesy of Bruce Macintosh and Christian Marois for the GPI team

LLNL-PRES-529871

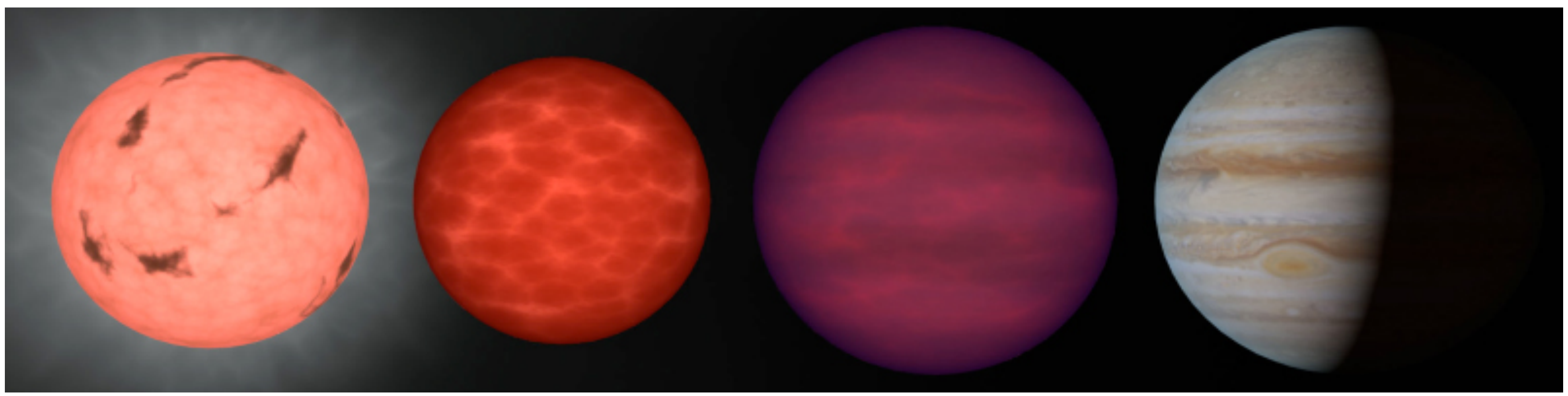
This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Talk outline

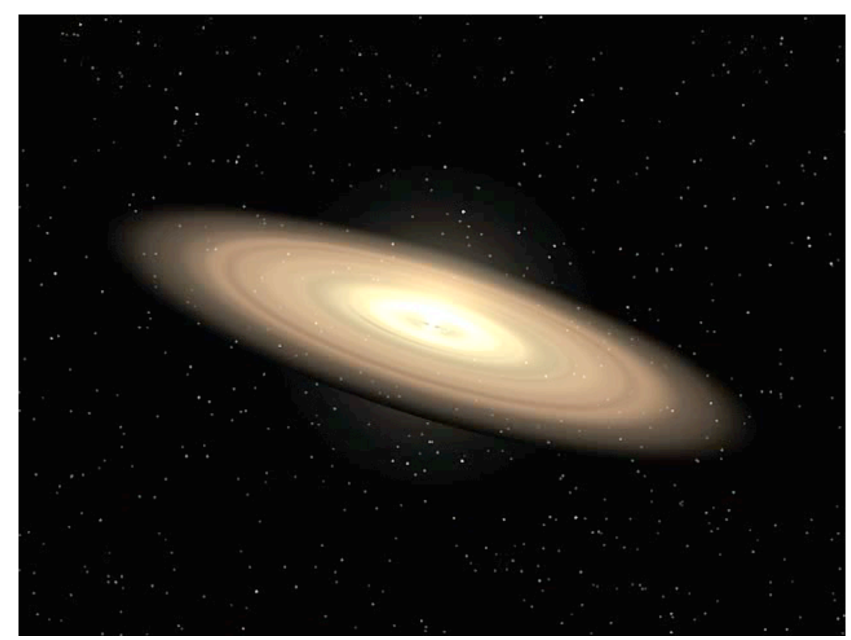
- Science goals and the design of GPI
- How do we estimate performance?
- AO-centric simulation
- Fresnel/Talbot simulations
- The CAL system
- The IFS and the data pipeline

GPI is a science experiment

- Our science team recently was allocated 890 hours for a three-year survey for 600 target stars



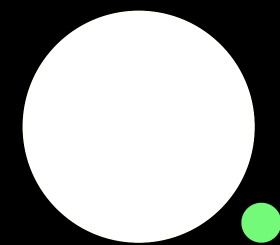
- How do planets form and evolve? (core accretion vs. disk instability)
- What are planetary atmospheres like?
- How do planets migrate? What is their dynamical evolution?



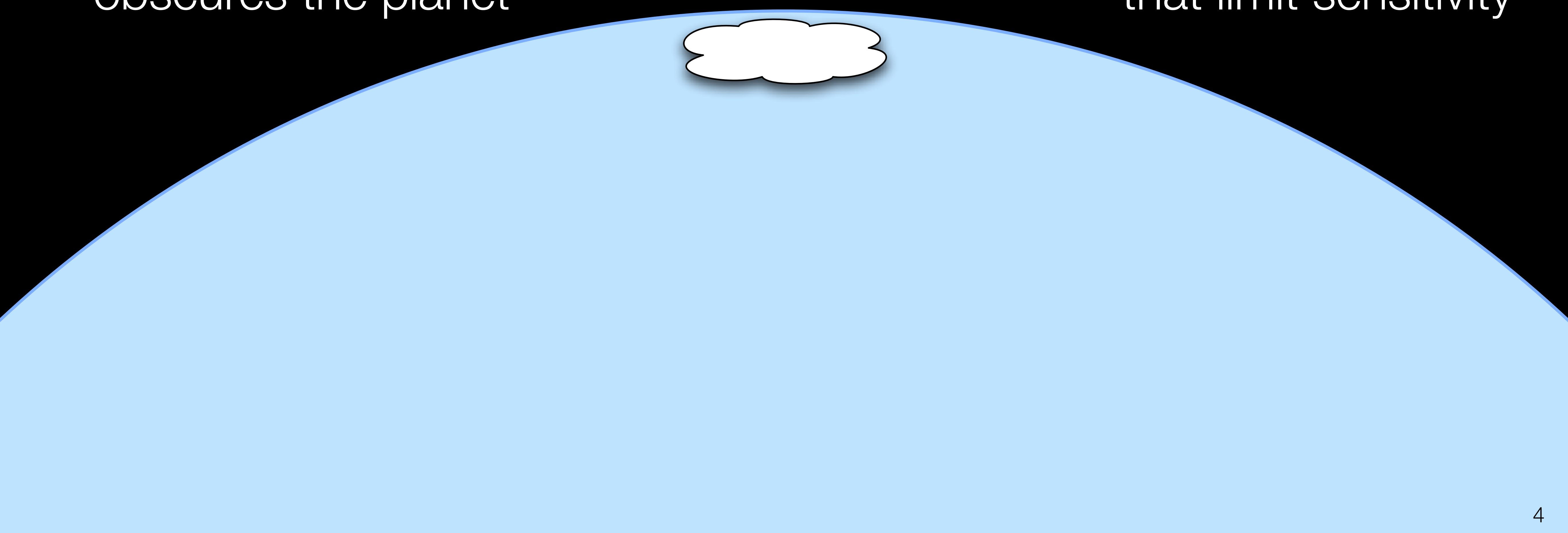
Images from Robert Hurt; NASA Spitzer

GPI has 4 essential tasks and units

- Remove distortions caused by atmospheric turbulence
- Suppress diffraction from the star that obscures the planet



- Use multi-wavelength to aid detection and provide information about the planet
- Fix quasi-static errors that limit sensitivity



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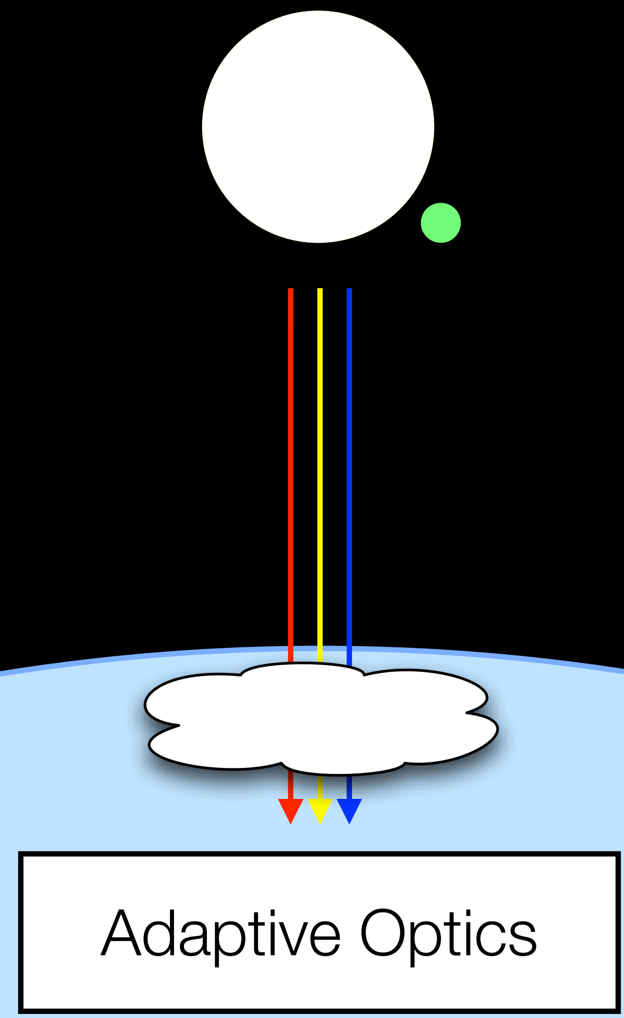

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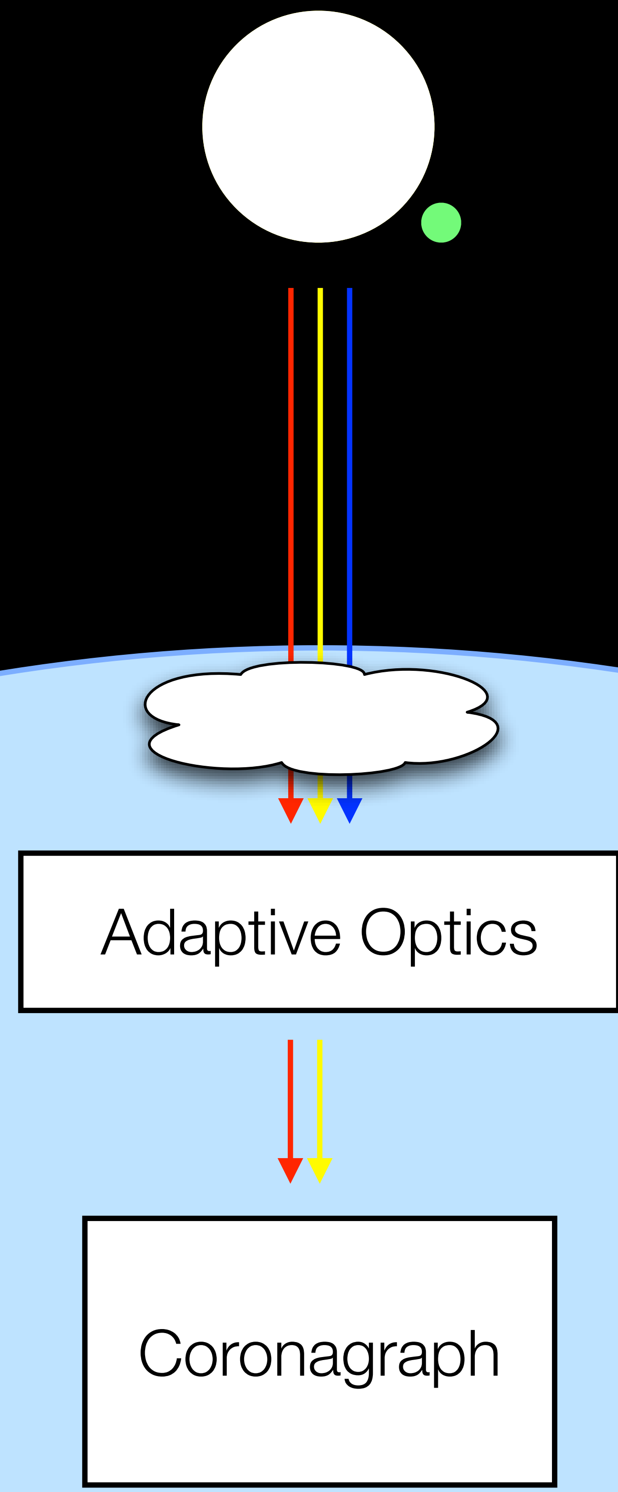

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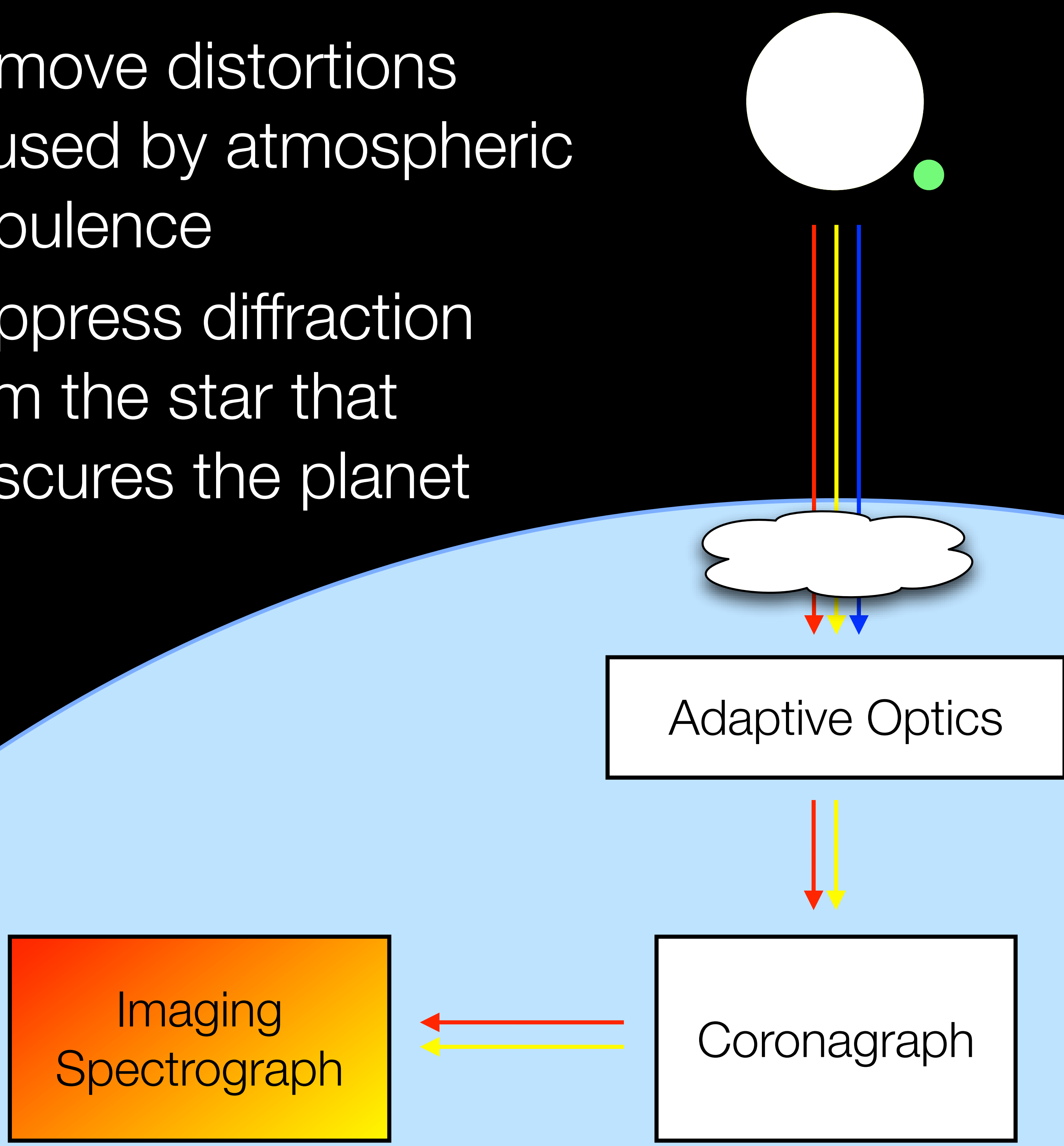

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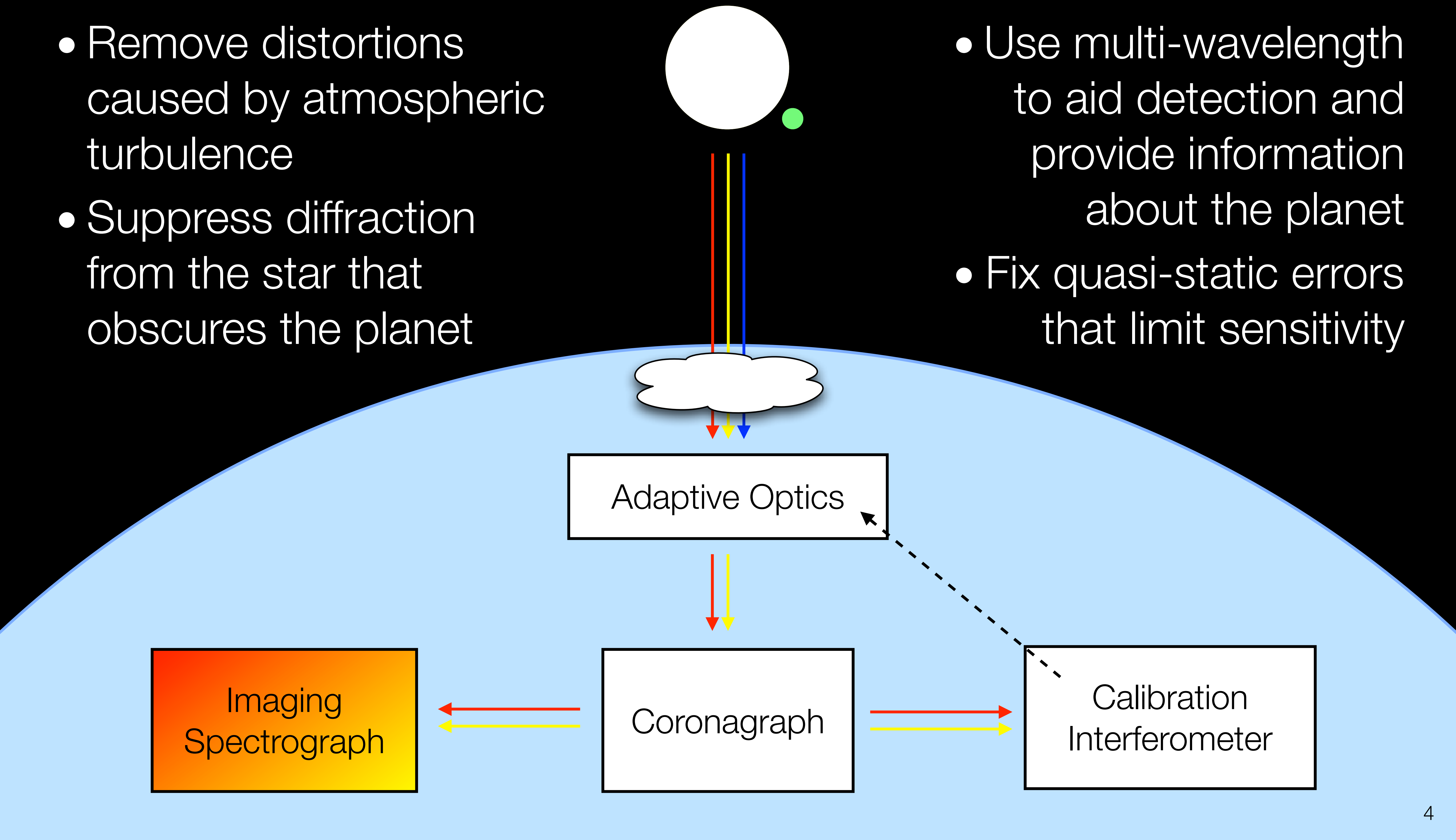
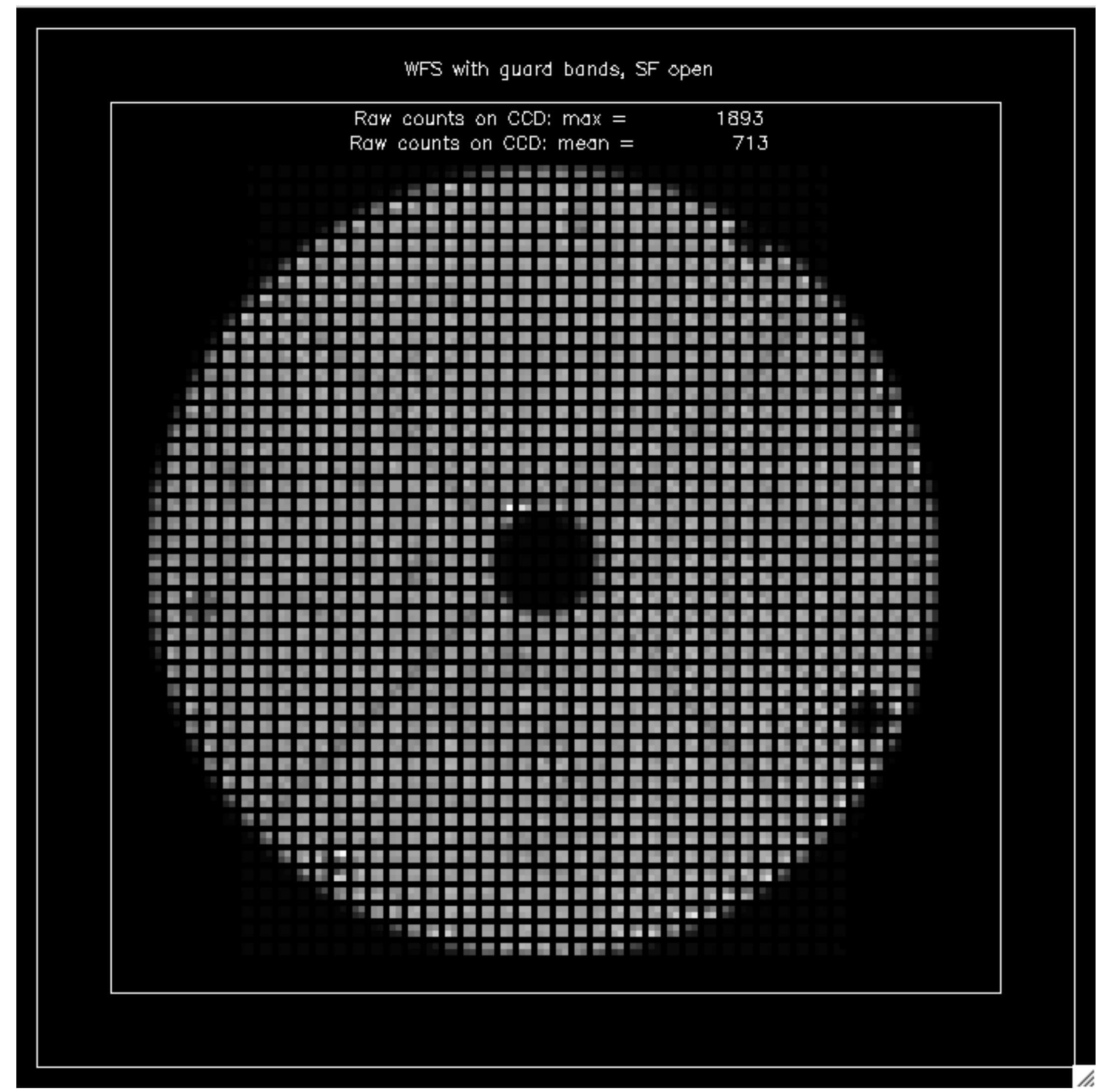


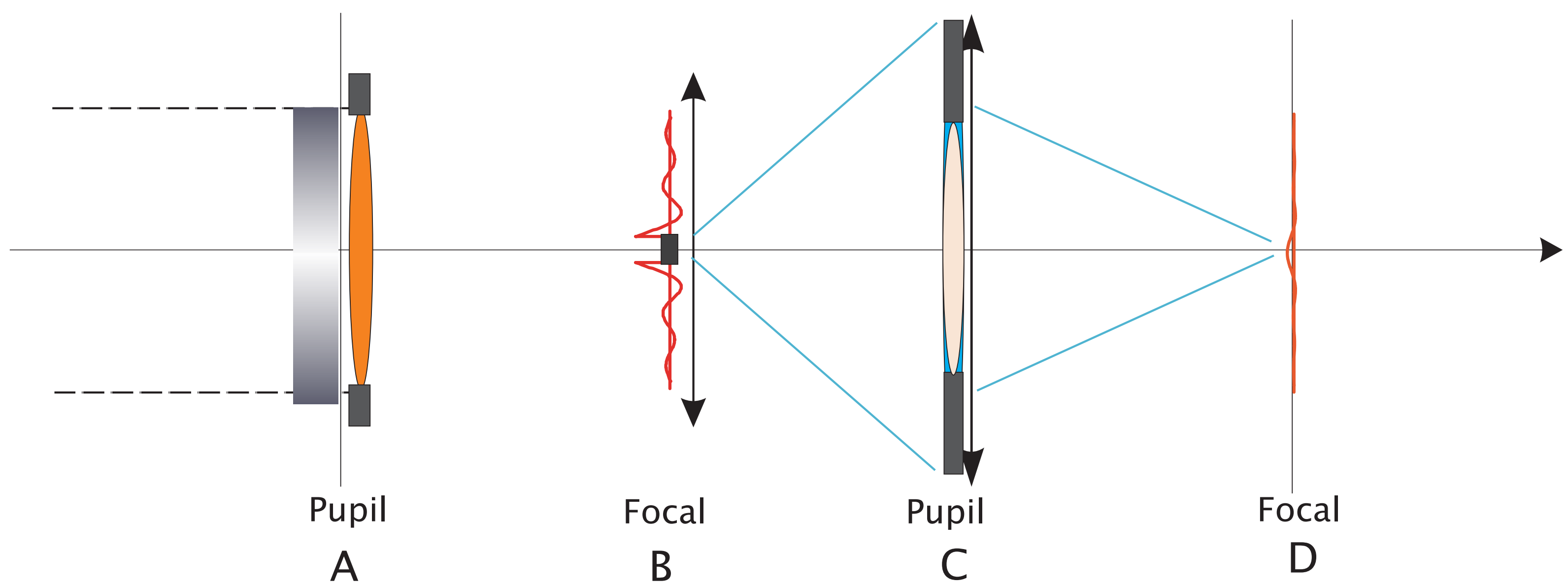
GPI is designed for high-contrast imaging

- Compared to current general purpose AO, GPI has:
  - **10 times the actuator density per area (18 cm spacing instead of 56-60 cm)**
  - **< 5 nm uncalibrated non-common path error**
  - **a spatially filtered wavefront sensor to produce a “dark hole”**
- Compared to other “extreme” AO systems (Sphere, PALM-3K), GPI has:
  - **a MEMS deformable mirror**
  - **Fourier-transform-based, computationally efficient wavefront reconstruction and self-optimizing control**



APLC improves Lyot design

- Apodization allows more efficient destructive interference, providing better cancellation in Lyot plane
- Better throughput and angular resolution
- Built by AMNH (PI: Oppenheimer)



Thanks to R. Soummer for the figure.
See several references, including: Aime et al (2002), Soummer et al (2003) and Soummer (2005)

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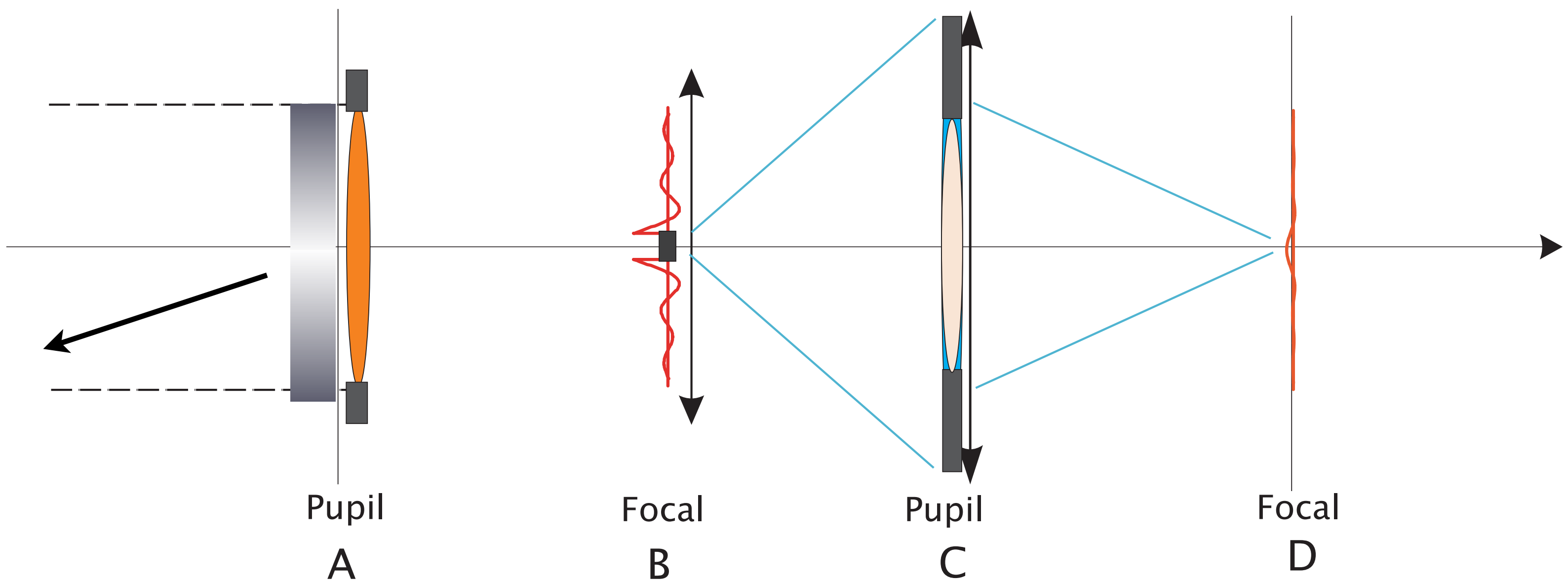

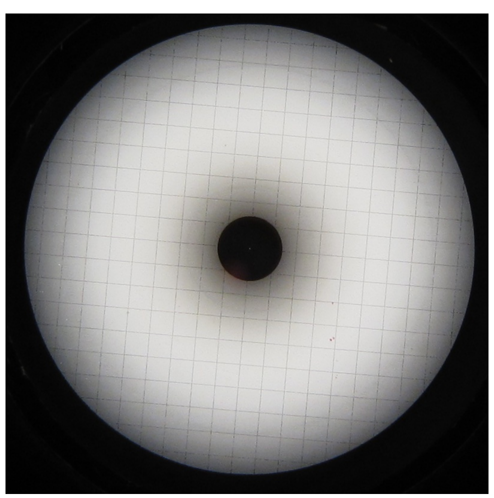

Apodizer transmission

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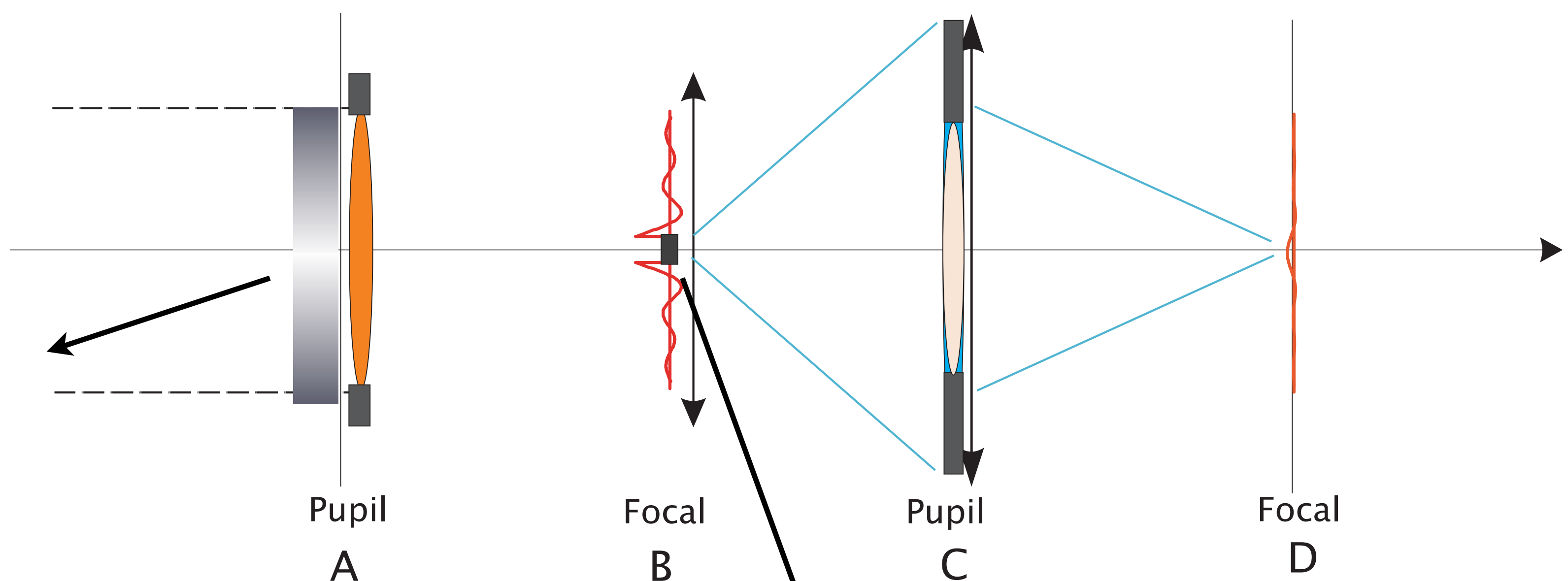
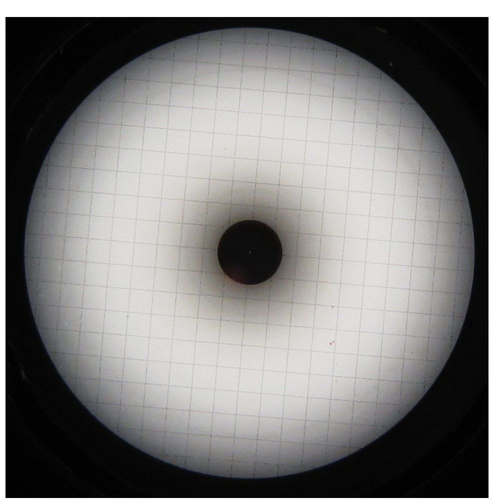
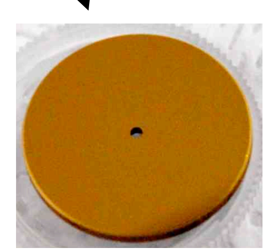




Apodizer transmission

Hard-edge stop
Diameter ~5 λ/D



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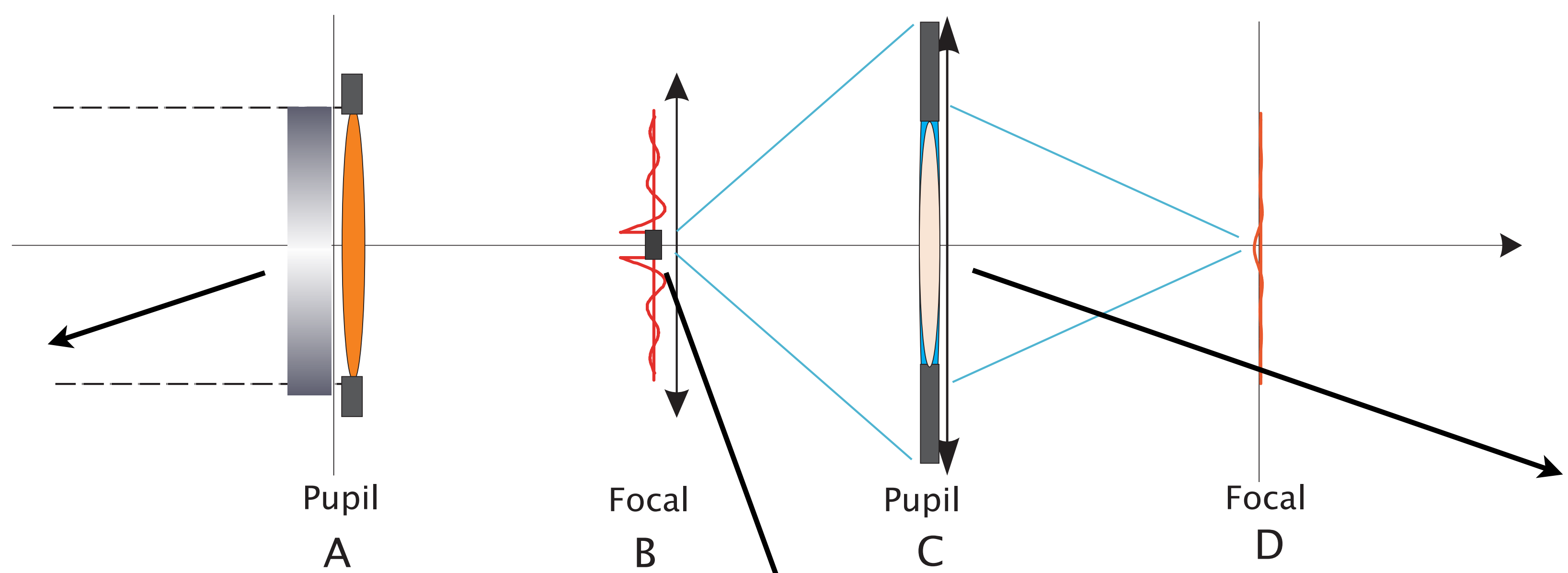

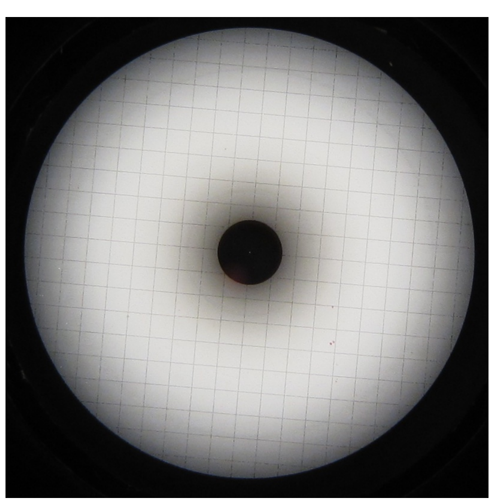

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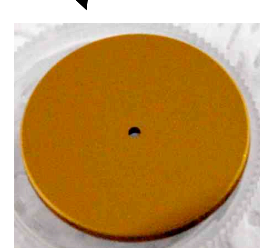

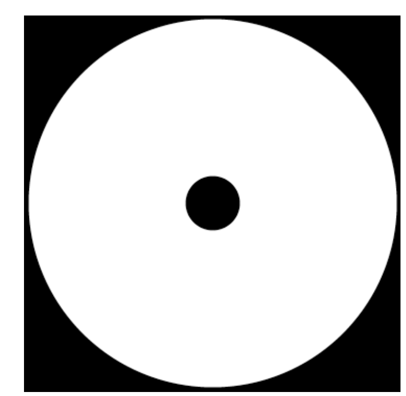

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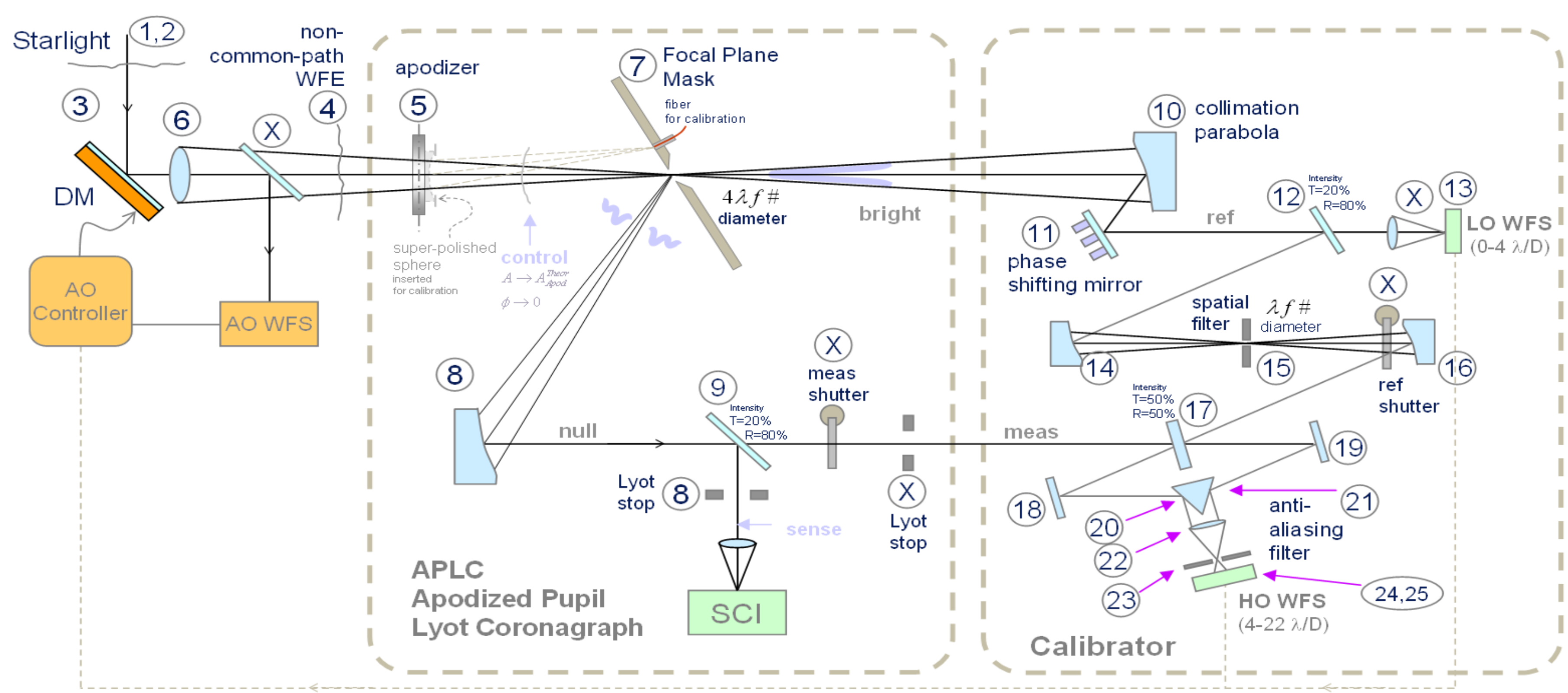
Cal system measures quasi-static errors

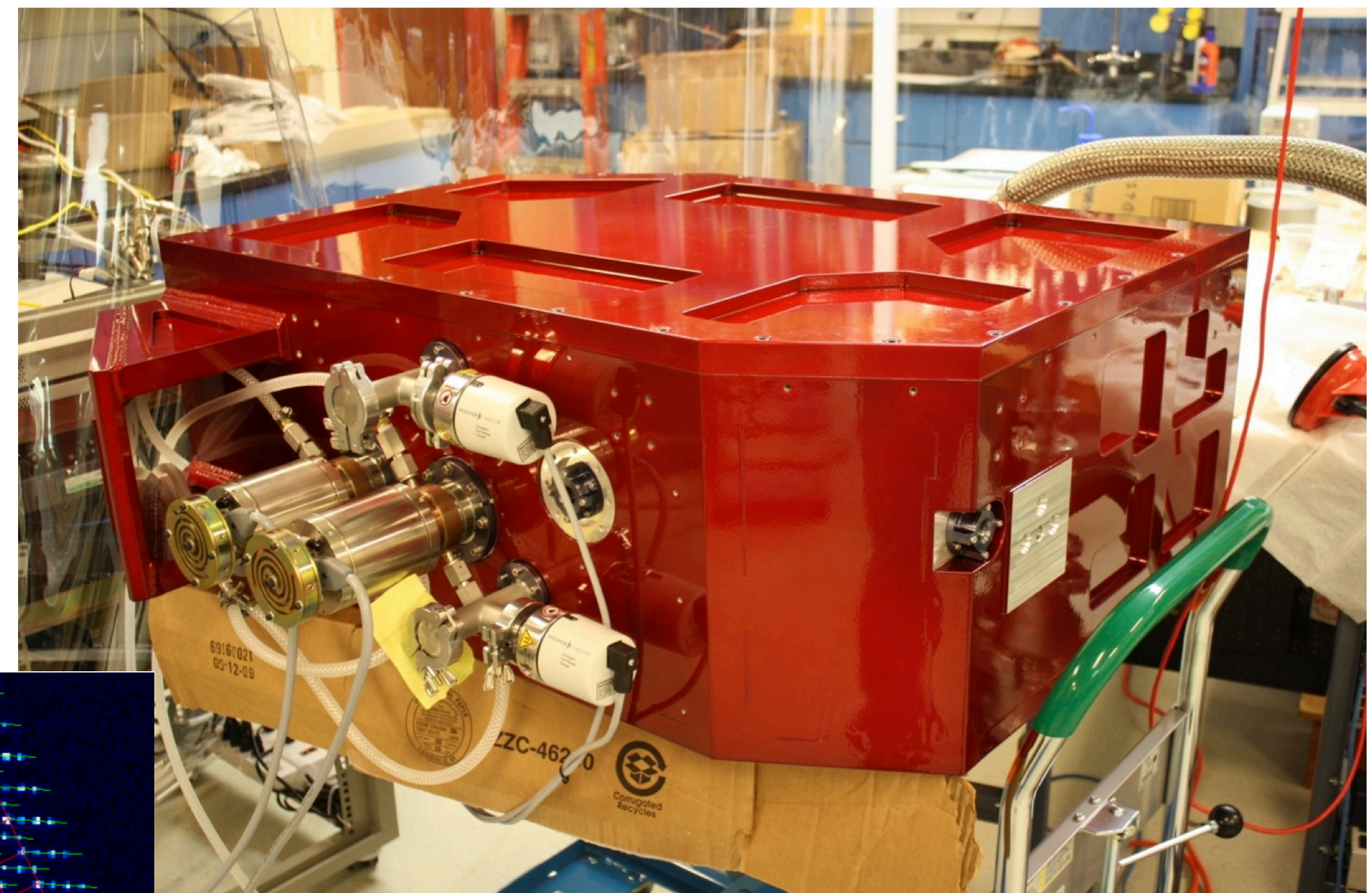
- Calibration system coupled with APLC
- LOWFS uses light from reference arm for low-order modes
- HOWFS is white-light, phase-shiting interferometer using reference and science light
- Built by JPL (PI: Wallace)

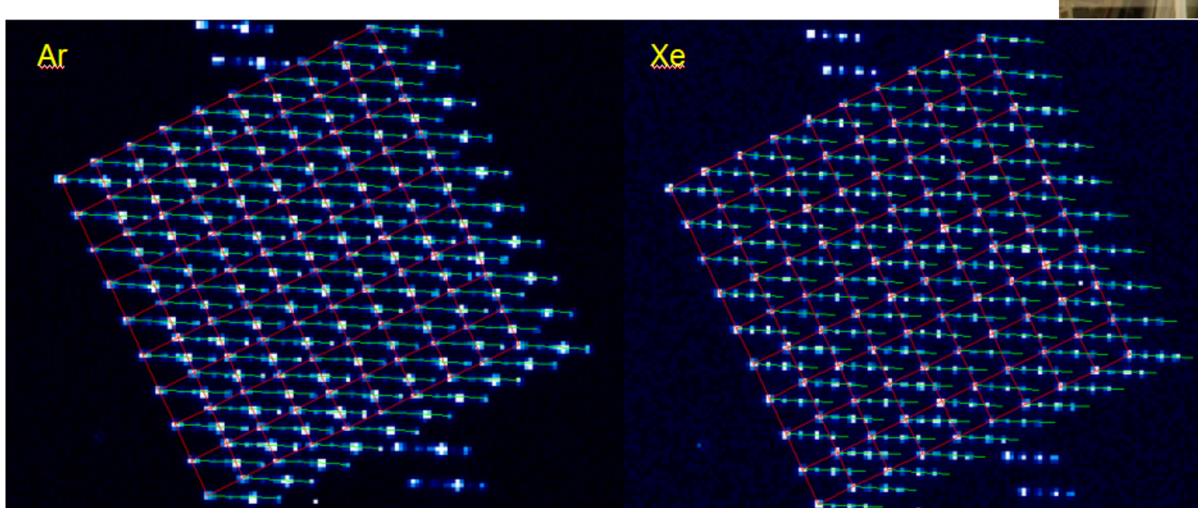


Schematic courtesy of Kent Wallace (JPL)

Dedicated hyperspectral imager

- Lenslet-based Integral Field Spectrograph
- R = 34 to 80 from Y to K
- 2.8” x 2.8” FoV
- 0.014” per pixel
- Built by UCLA (PI: Larkin) with U. Montreal and Immervision

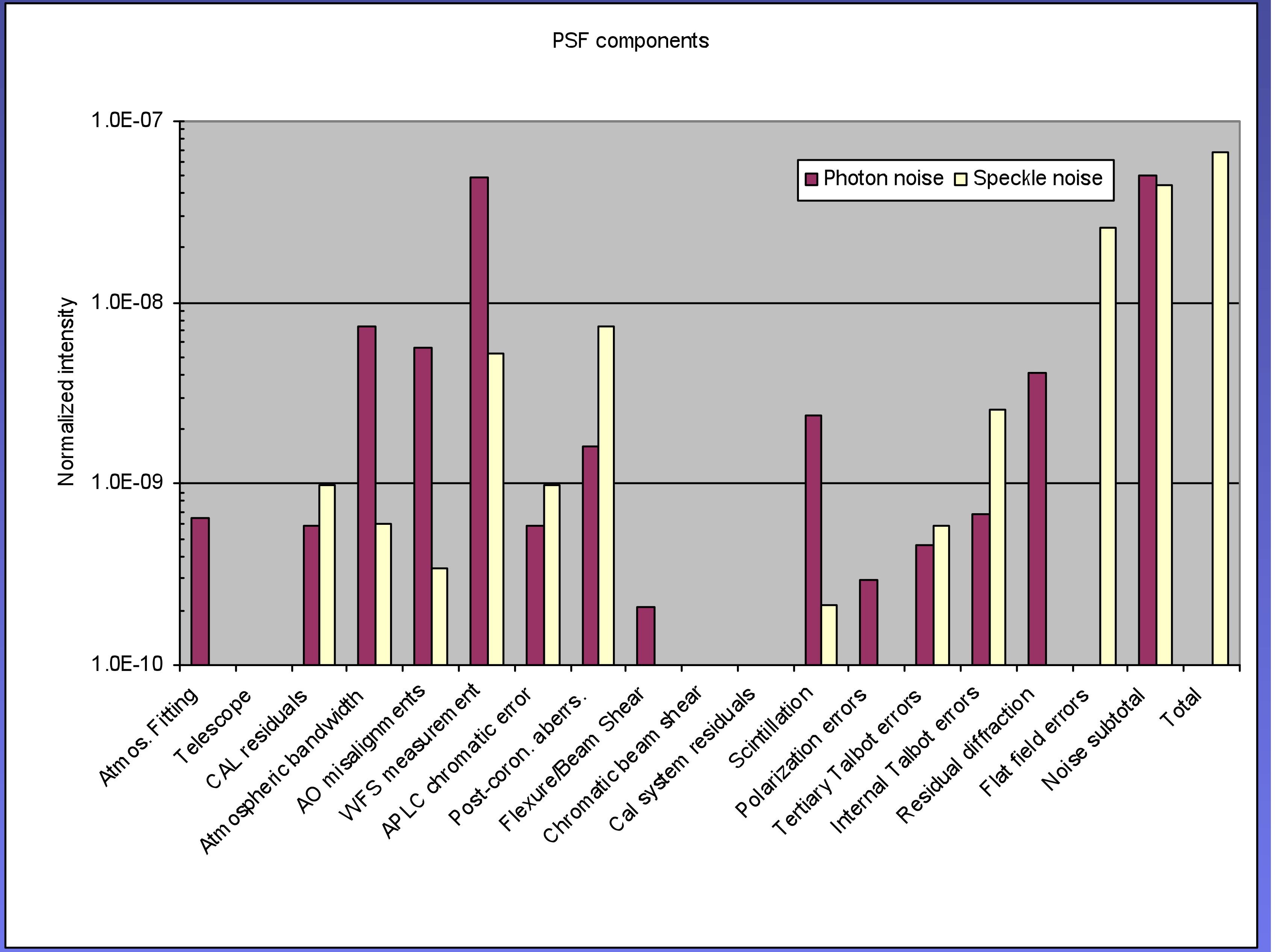




Optics test images courtesy of U. Montreal;
IFS photo courtesy of UCLA

Conceptual contrast error budget

- Initial performance specs set with analytic error budget in contrast
- Requirements refined through simulations as design progressed
- Req. 1: static and atmospheric speckle noise equal in a 1-hour exposure
- Req. 2: suppress speckle noise to photon noise level through multi-wavelength imaging



Macintosh

Friday, February 17, 2012

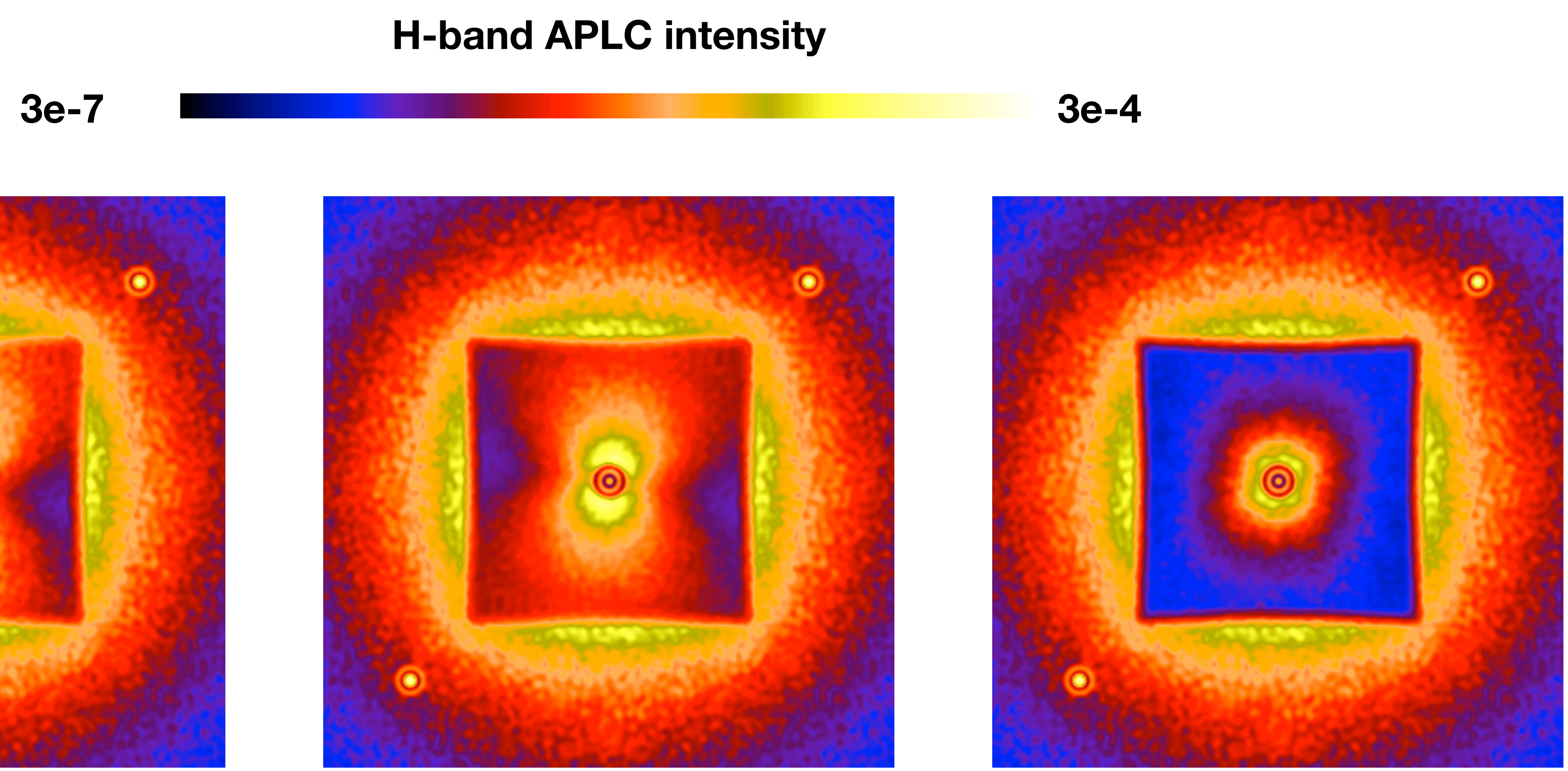
The AO simulator is very detailed

- Uses Fourier optics, in particular Fraunhofer propagation
- Multiple layer, frozen-flow, Kolmogorov atmosphere
- LSI Woofer-Tweeter mirrors, with some non-linearities (e.g. saturation) incorporated
- All AO control algorithms fully implemented and data-driven
- Spatial filter simulated with Fourier optics over WFS light
- Quadcell Shack-Hartmann using Fourier optics and CCD characteristics
- Fundamental AO relay misalignments (e.g. centering)

- Individual modules were fully validated against analytic or semi-analytic results

Algorithms and performance predictions

- Simulation designed to give thorough testing to new AO technologies and algorithms for GPI
- Incorporates APLC to give estimated PSFs for short exposures



[for comparison]
Uniform modal gains

[baseline]
Optimized modal gains

[goal]
Predictive control

GPI CDR results

PSD approach to AO performance

- In addition to individual module validations, we wanted an over-all "sanity check"
- AO simulator takes too long; need something faster for science team

- Approximate the PSF with the PSD term of the "PSF expansion"
- Several treatments exist (Ellerbroek; Guyon; Jolissaint)

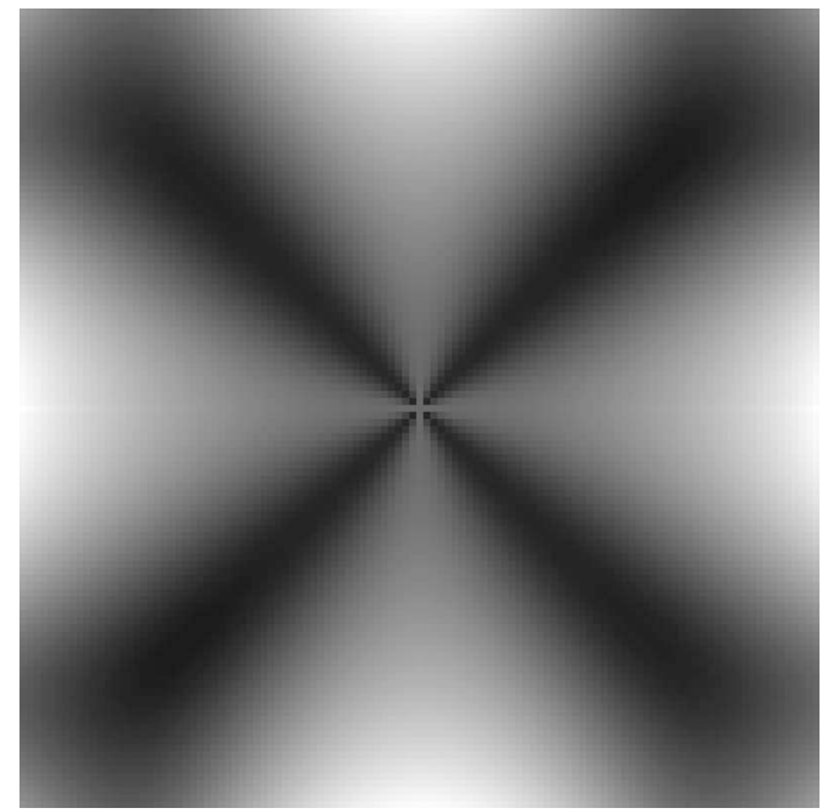
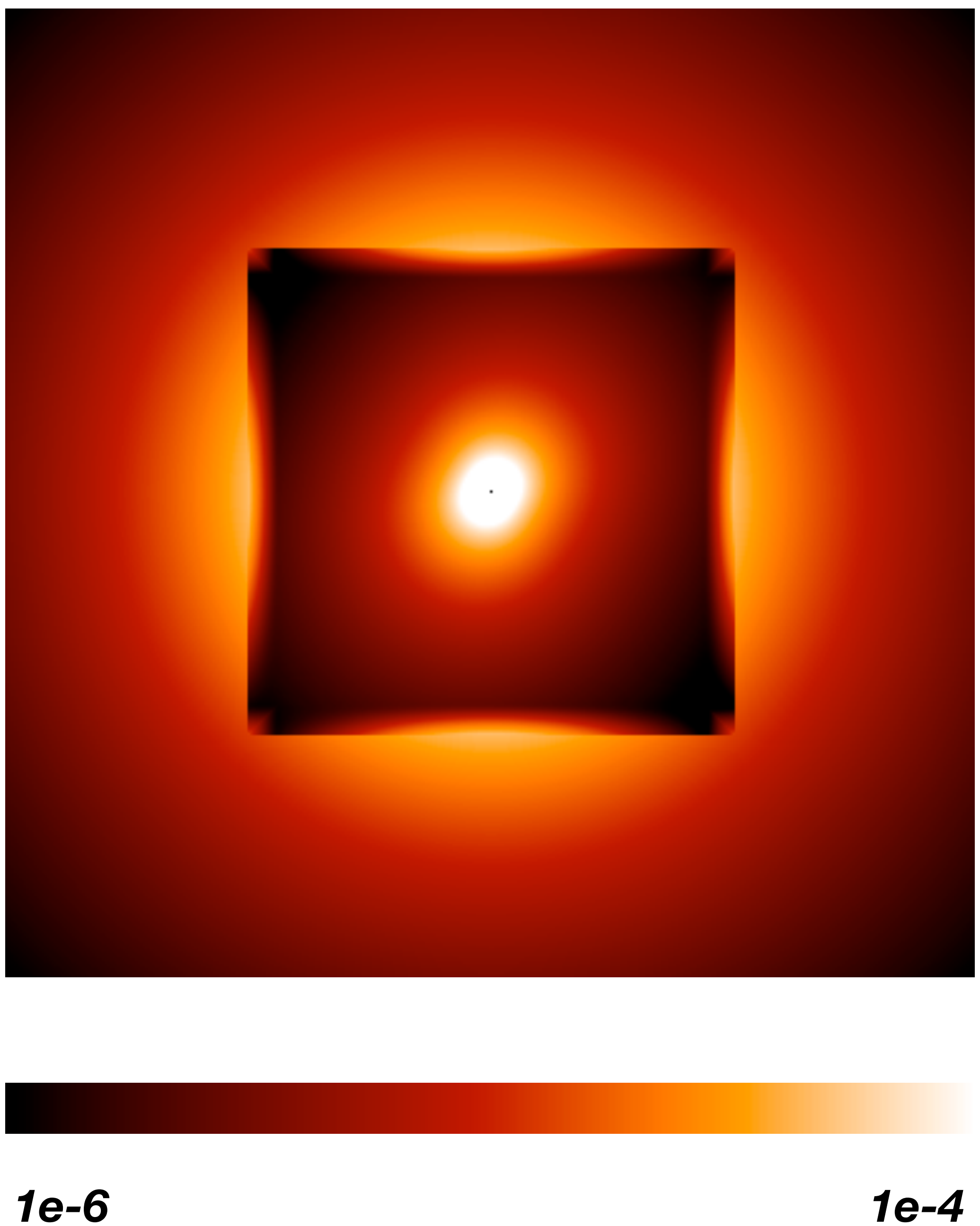


Fig. 2. Aliasing power spectrum (1/8 power-law scaling) within the LF domain; see parameters in Table 1.

Figure from L. Jolissaint, J.-P. Véran, and R. Conan, "Analytical modeling of adaptive optics: foundations of the phase spatial power spectrum approach," J. Opt. Soc. Am. A ***23****, 382–394 (2006).*

Validated GPI monte carlo simulator



I=6, five-layer 14.5 cm r0 atmosphere, 2 kHz, Optimized-gain controller, 700-900 nm WFS, APLC at 1.625 microns, 5 second exposure

- Started from Guyon method (ApJ 2005)
- Made additions to model the unique features of GPI AO
- Found very good agreement between short-exposure monte carlo PSFs and PSD approach

- PSD code is used by science team

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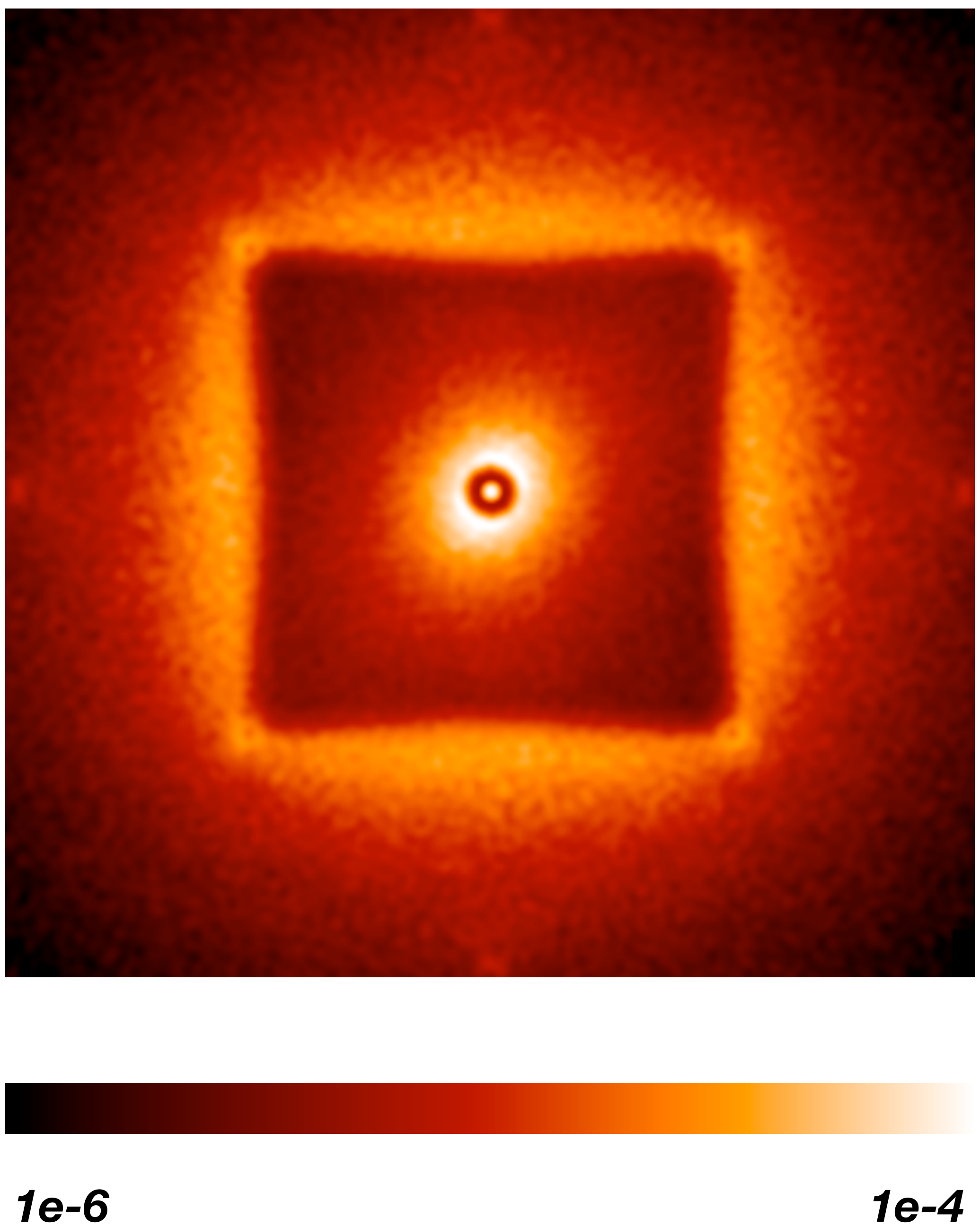

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Our AO simulator can't do everything

- No Fresnel propagation between phase screens in atmosphere (but scintillation negligible)
- Idealized pupil-plane/focal-plane model of AO relay: no out-of-plane optics!
- Simulation is achromatic
- Individual runs are limited by phase screen size to ~ 4 seconds

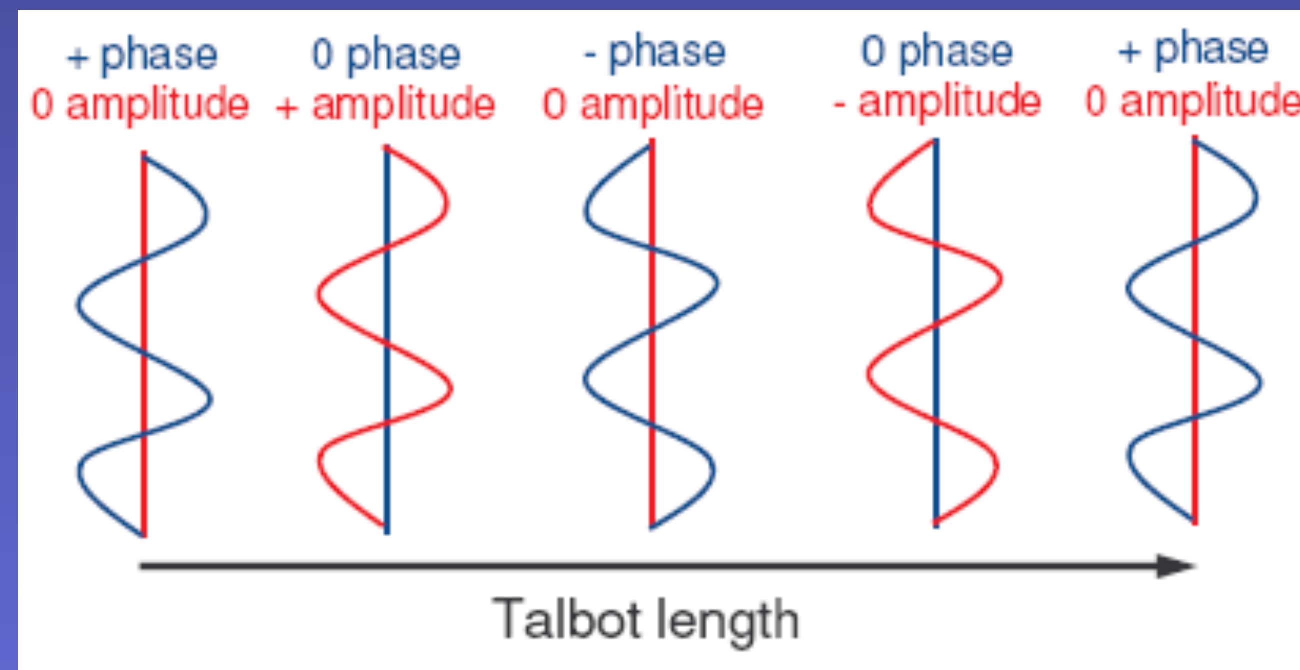
- How to consider these other terms?
- Will not be done in the AO monte carlo code

Talbot imaging: phase-induced ampl. errors

-From Fresnel propagation

-Valid for:
- -Infinite wavefronts
- -Collimated beam
- -Small aberrations

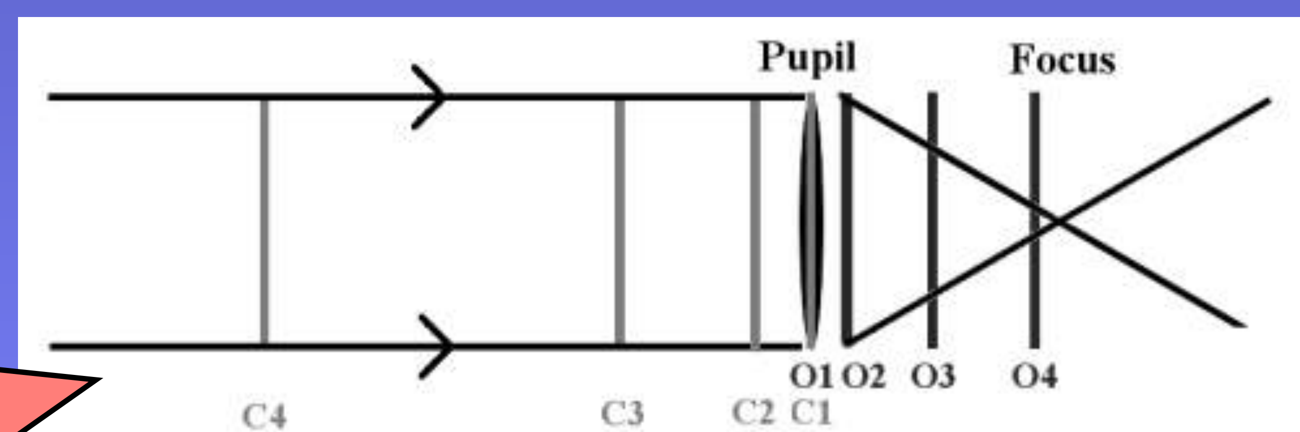
-Easy to implement



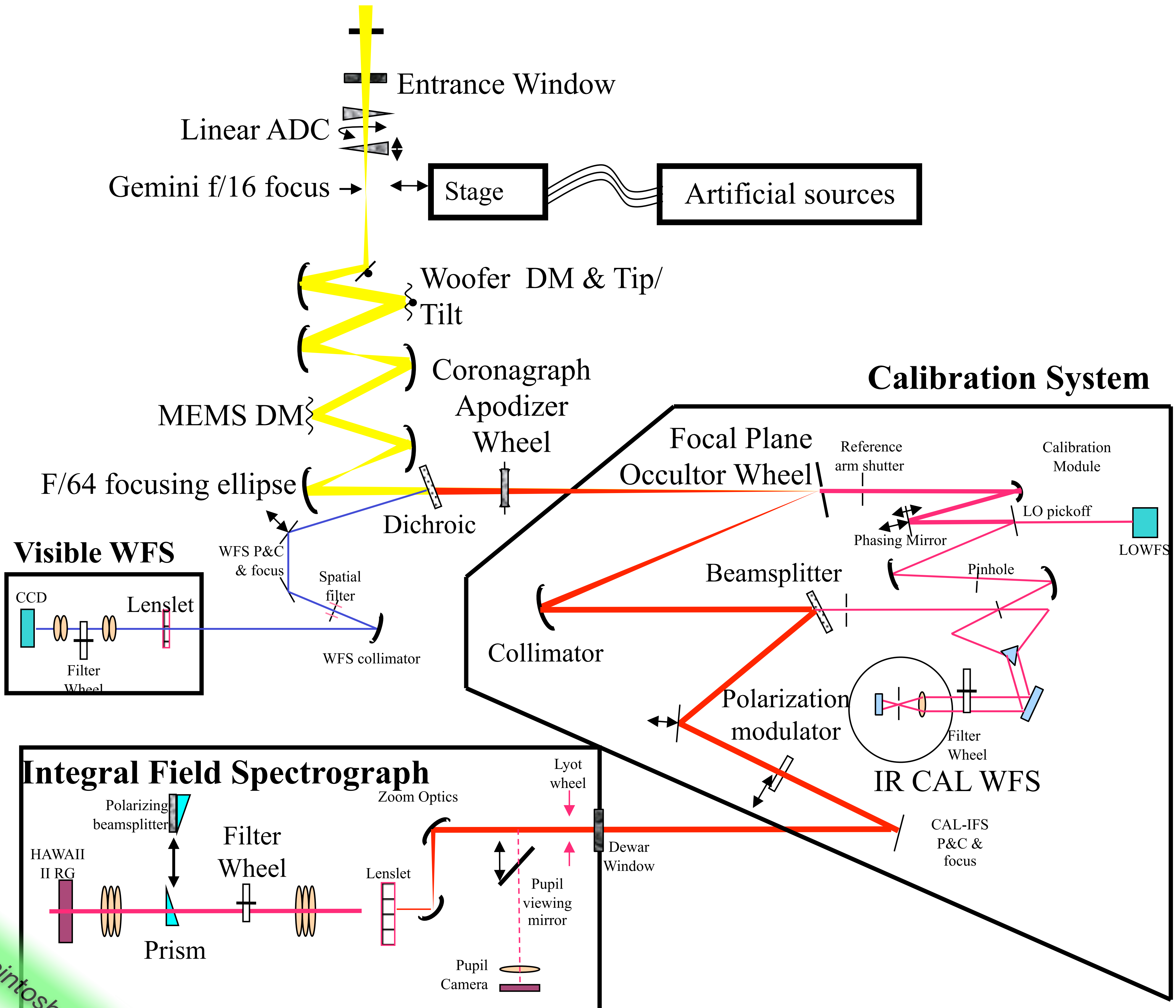
-A pure phase is oscillating between pure phase and a pure ampl. aberration over a length equal to:

$$\tau_L = 2\Lambda^2/\lambda$$

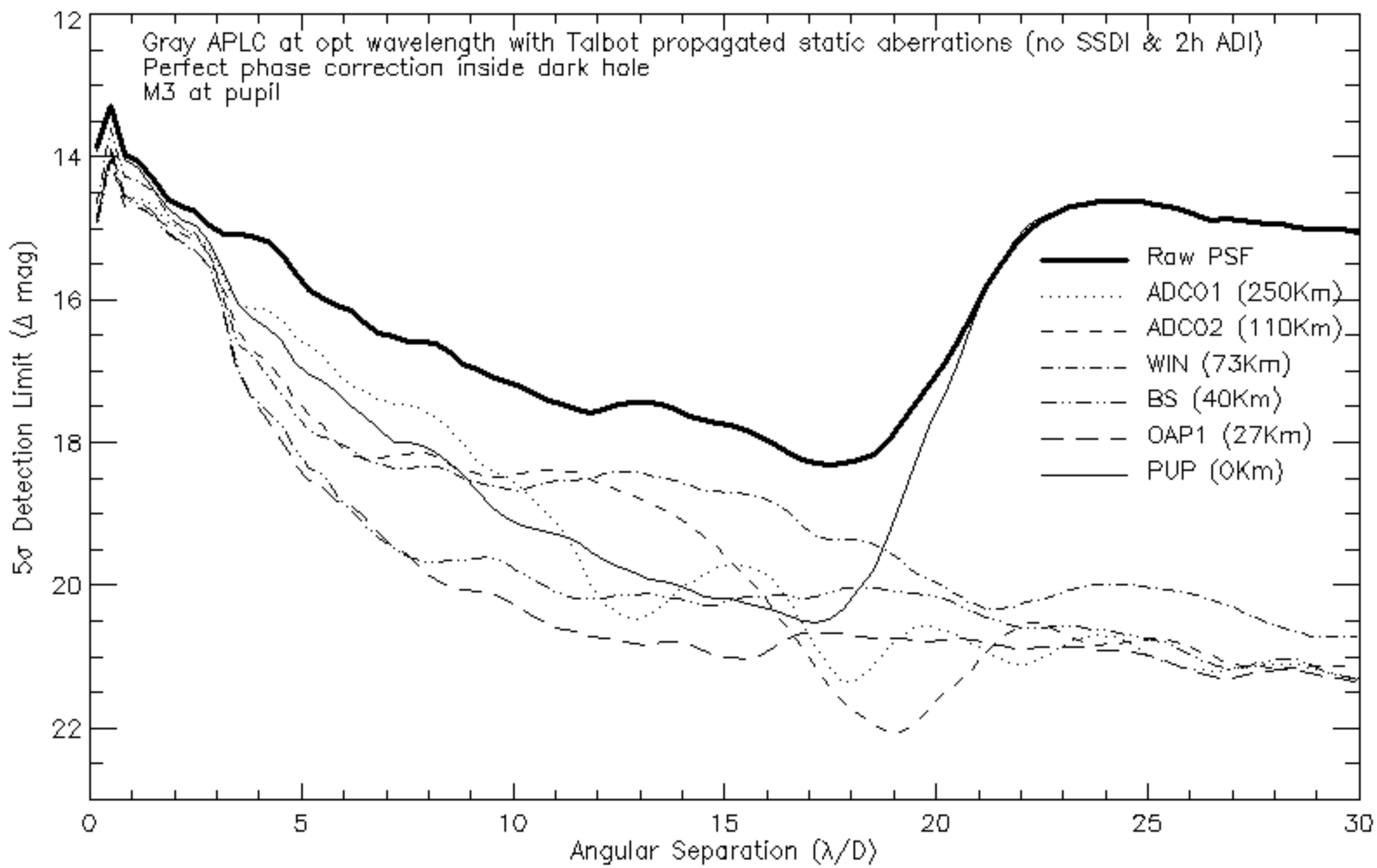
GPI sensitive!



where Λ is the aberration spatial period.


Entrance Window
Linear ADC
Gemini f/16 focus
Stage
Artificial sources
Woofer DM & Tip/ Tilt
Coronagraph Apodizer Wheel
MEMS DM
F/64 focusing ellipse
Dichroic
Calibration System
Focal Plane Occultor Wheel
Reference arm shutter
Calibration Module
LO pickoff
LOWFS
Phasing Mirror
Pinhole
Beamsplitter
Collimator
Polarization modulator
Filter Wheel
IR CAL WFS
CAL-IFS P&C & focus
Visible WFS
CCD
Lenslet
Filter Wheel
WFS P&C & focus
Spatial filter
WFS collimator
Integral Field Spectrograph
Polarizing beamsplitter
HAWAII II RG
Filter Wheel
Prism
Zoom Optics
Lyot wheel
Lenslet
Dewar Window
Pupil viewing mirror
Pupil Camera

GPI raw static contrast from each plane



Conclusions

Gemini Planet Imager

Imageur de Planètes pour Gemini

Limiting magnitude (for AO): I-mag < 9-10

Spectral bands: Y, J, H, K

Spectral resolution: IFS with R~45 at H (~same at J and K-band)

Broadband polarimetric mode

FOV: 2.9” x 2.9”

Inner working angle: 2.8 lambda/D radius

Dark hole size: 21 x 21 lambda/D

Contrast: up to 10^{-7} from PSF peak intensity

First light: December 2010

Tolerance Analysis

- CAL Residual less than ~3nm RMS MSF.
- Entrance window needs to be clean.
- Spider Lyot mask os no more than ~3%.
- Reach 10^7 photon limited contrast at a few l/D in 1h integration time (goal) with SSDI & ADI.

To be Continued...

SPIE 2010

Marois

End-2-End Fresnel Prog. II

Angry Photons Strike Back

How do we deal with AO-Cal interaction?

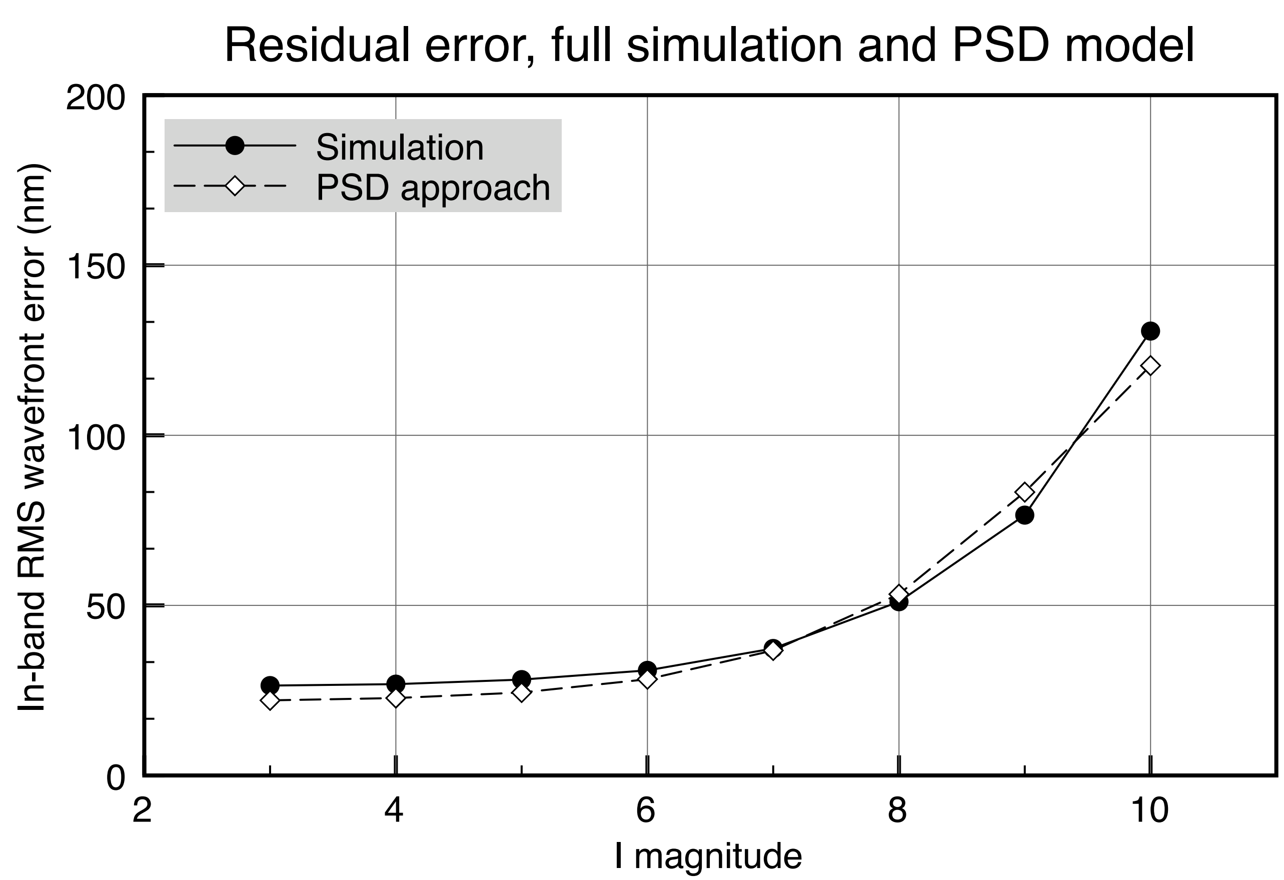
- GPI's calibration system will help correct static and quasi-static errors on the time scales of minutes
- Its measurements are used by the AO system

- Can't just simulate the Cal system and run the AO simulator for a 30-minute run!

- Instead we
  - **estimate residual AO error seen by the Cal system**
  - **use mechanical models to show growth of quasi-static errors through time (e.g. from flexure)**
  - **use Simulink to model the Cal system's slow closed-loop as implemented with AO references**

Simulation method: AO side

- Store AO telemetry (as for gain optimization and prediction)
- Evaluate residual error power temporal PSDs for
  - **specific low-order Fourier modes seen by the LOWFS**
  - **all the other Fourier modes seen by the HOWFS**
- Do this for all magnitudes of interest with OFC
  - **assume H-I = 0 for obtaining AO performance**

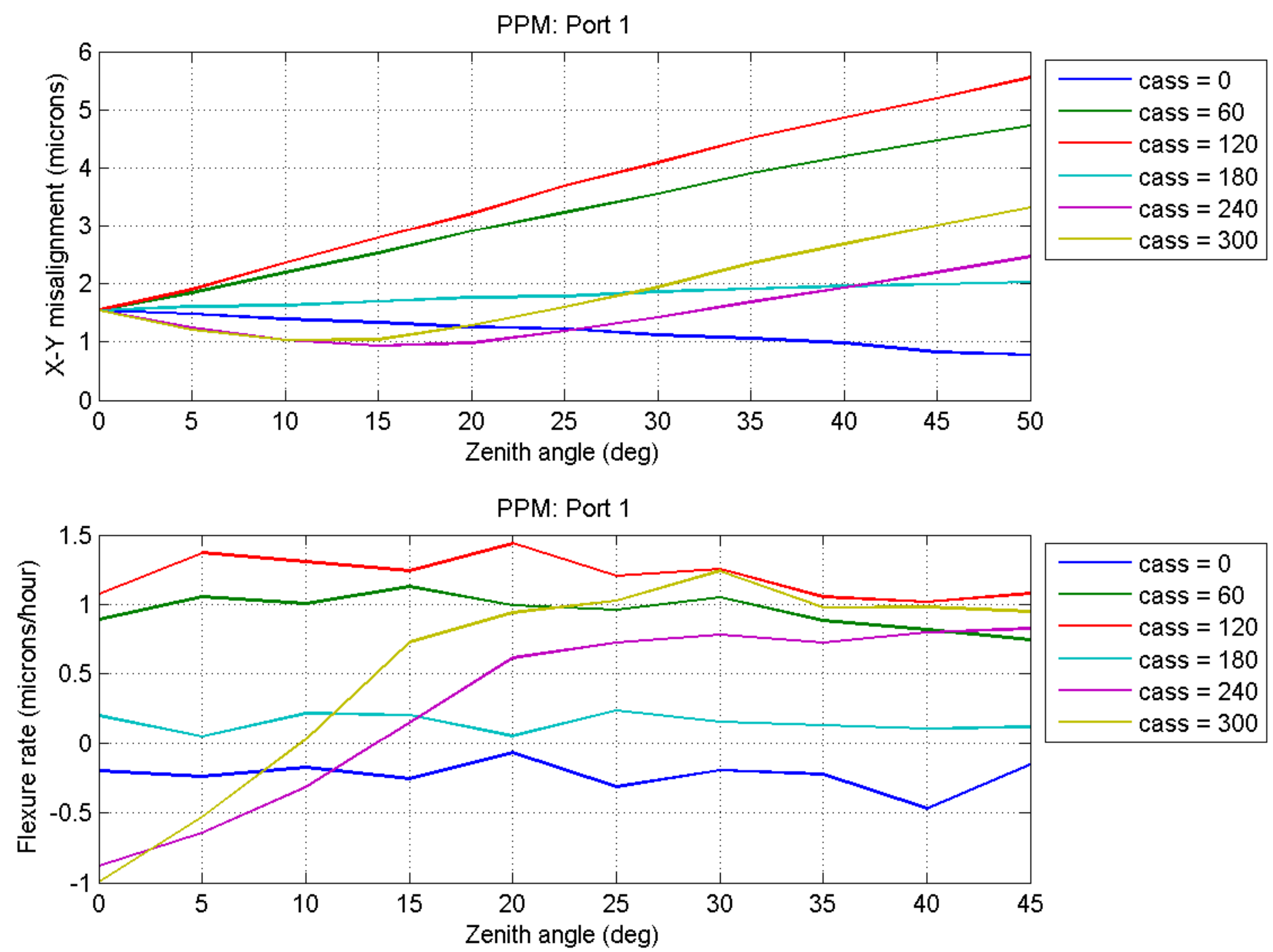


GPI CDR results

Defining the time-varying NCP errors

- Thermal flexure, gravity loading and atmospheric dispersion analysis to determine beam motion
- Convert into wavefront error given optics involved

NCP source	Max WFE (nm)	Max rate (nm/hr)
Flexure	1.0	0.4
Atm disp beam walk	2.2	1.6



Pupil centering on PPM (port 1), 15 deg/hr motion

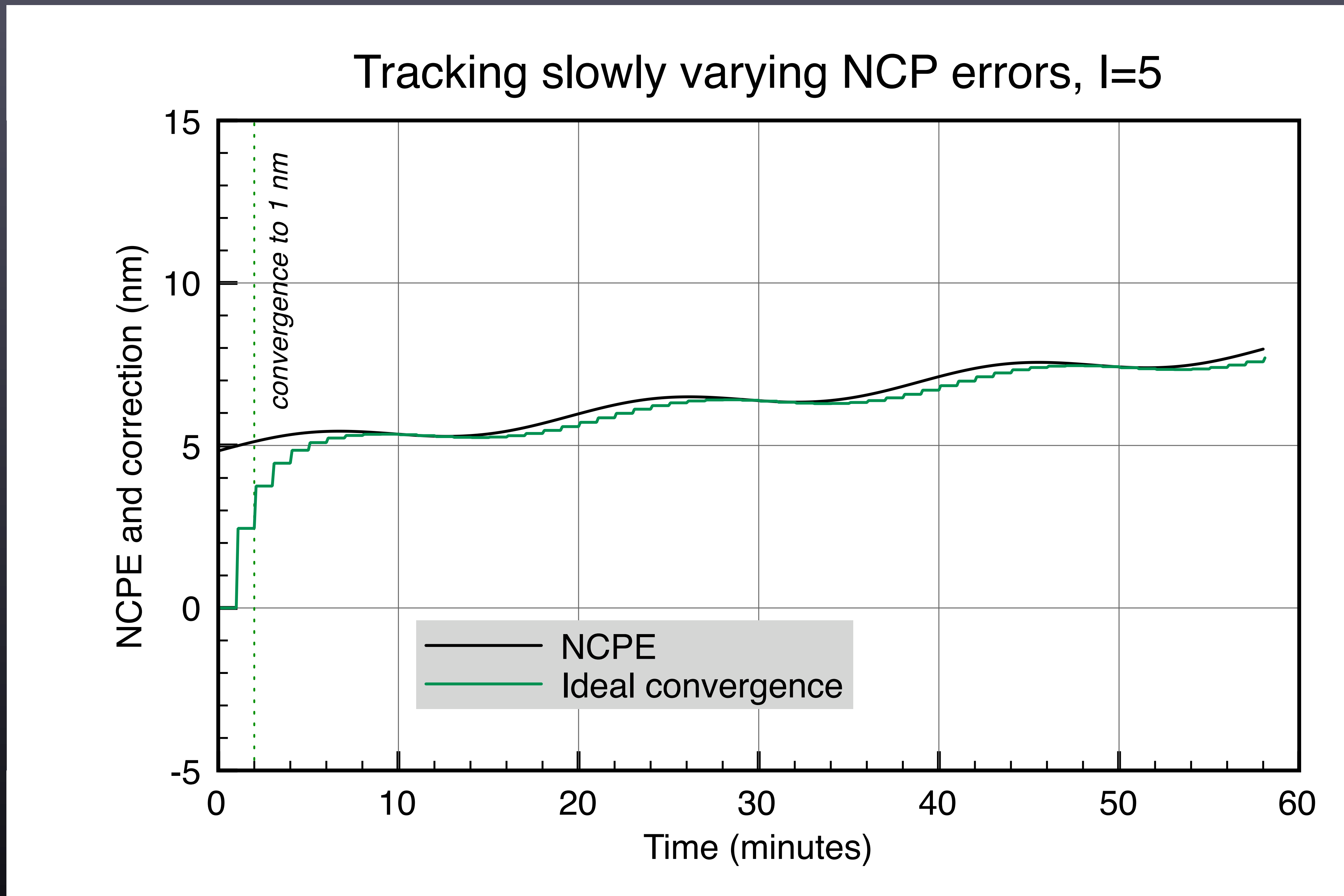
GPI CDR results

Simulation method: Calibration side

- Construct Simulink model (and Laplace model) based on flow diagram shown earlier
- Use TT/LOWFS/HOWFS noise variances per exposure as determined by JPL
  - **Assume slower updates achieved by averaging fast measurements [temp.white]**
  - **Assume CAL returns unbiased, gain = 1 measurement of NCP**
- Make deterministic NCP signal from twice GPI expected error
- Use temporal PSDs to generate AO residual signals
  - **HOWFS/LOWFS: AO residual from end-to-end simulation**
  - **TT: Gemini South P2/OIWFS median profile**
- Find Calibration update rate that meets tracking noise requirement given AO residual and Calibration noise
- Run Simulink to verify performance

GPI CDR results

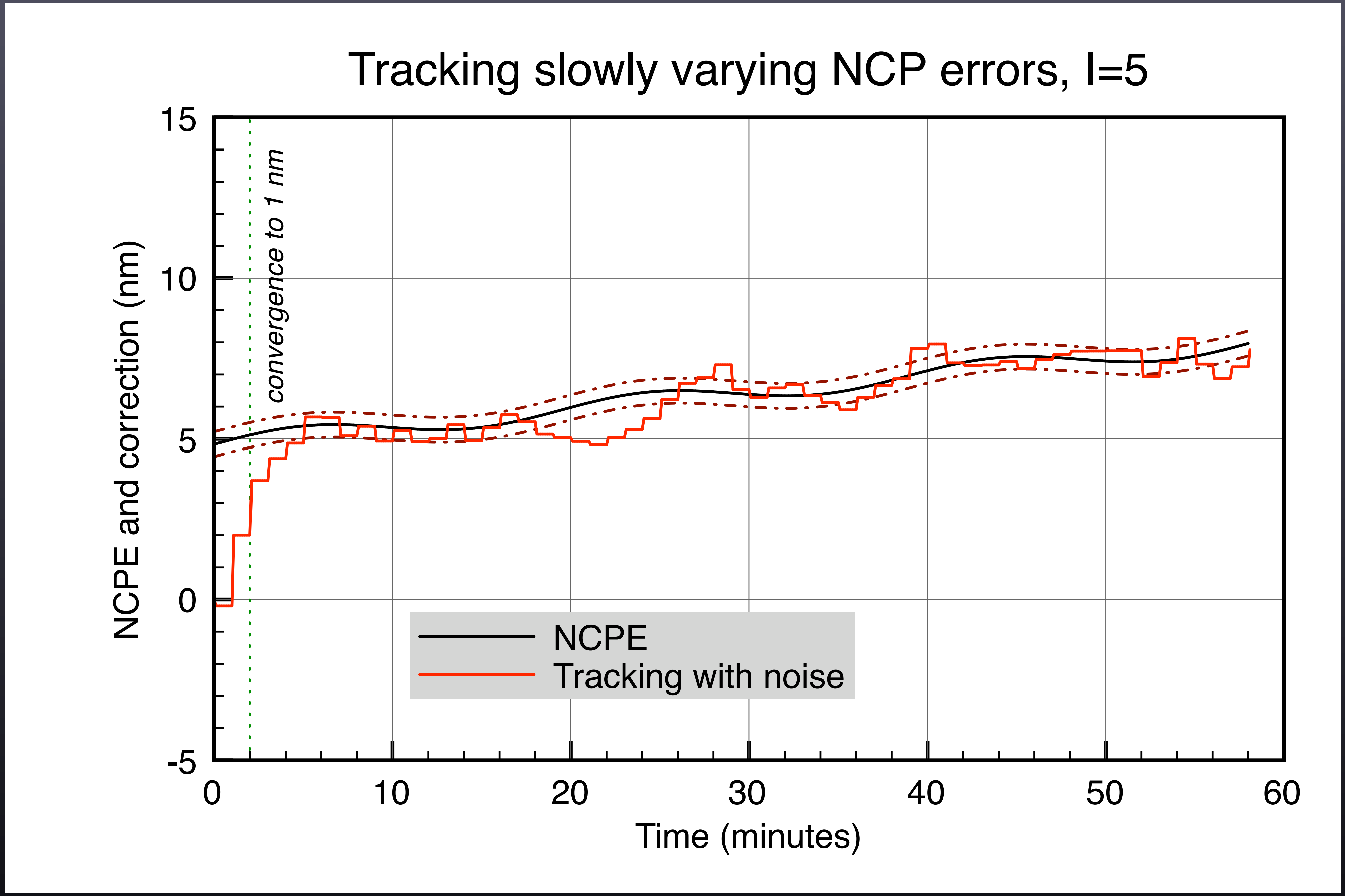
I=5, 1-minute updates, g=0.5, no noise



Convergence on initial NCPE

GPI CDR results

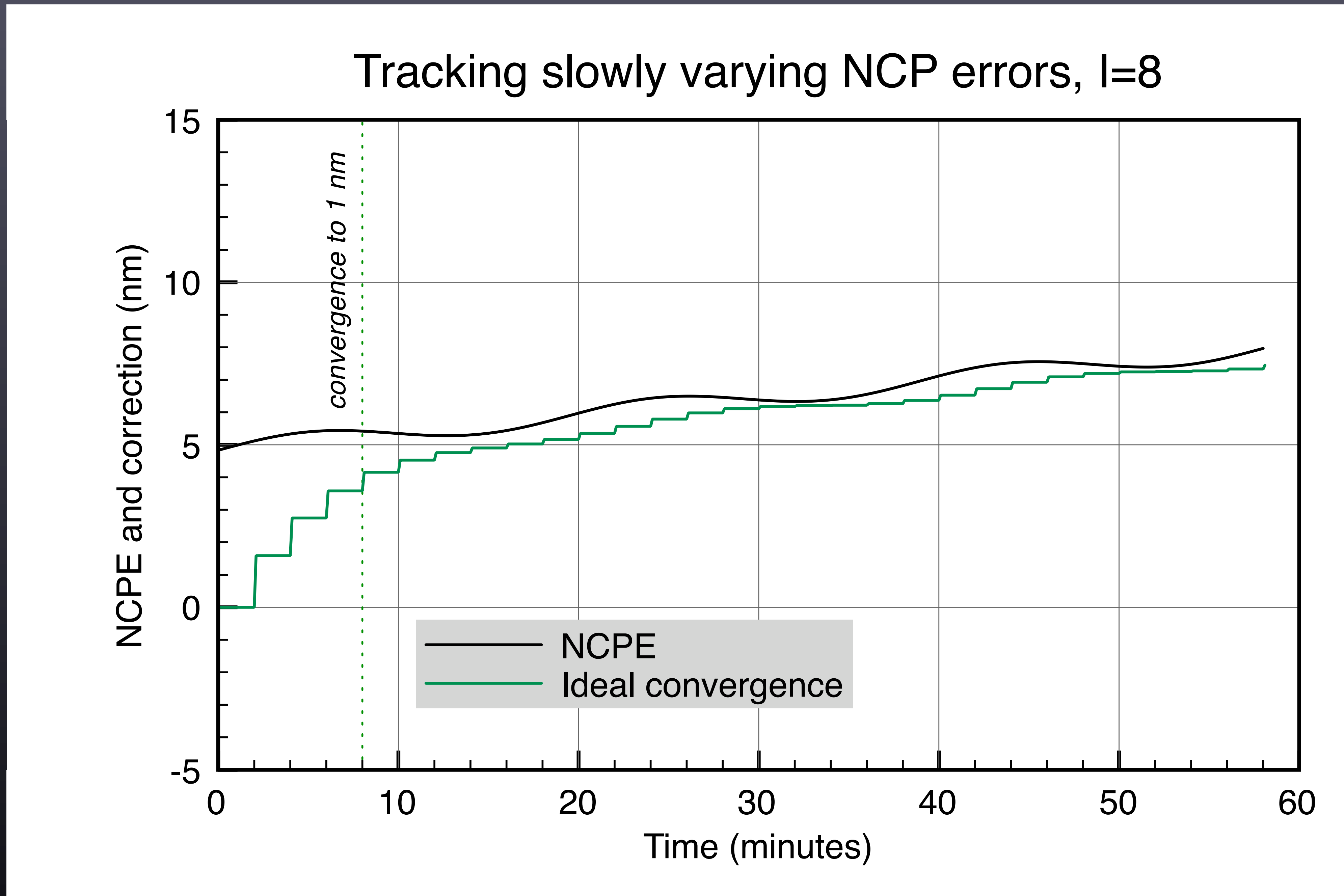
l=5, 1-minute updates, g=0.5



Tracking noise in steady state

GPI CDR results

I=8, 2-minute updates, g=0.32, no noise



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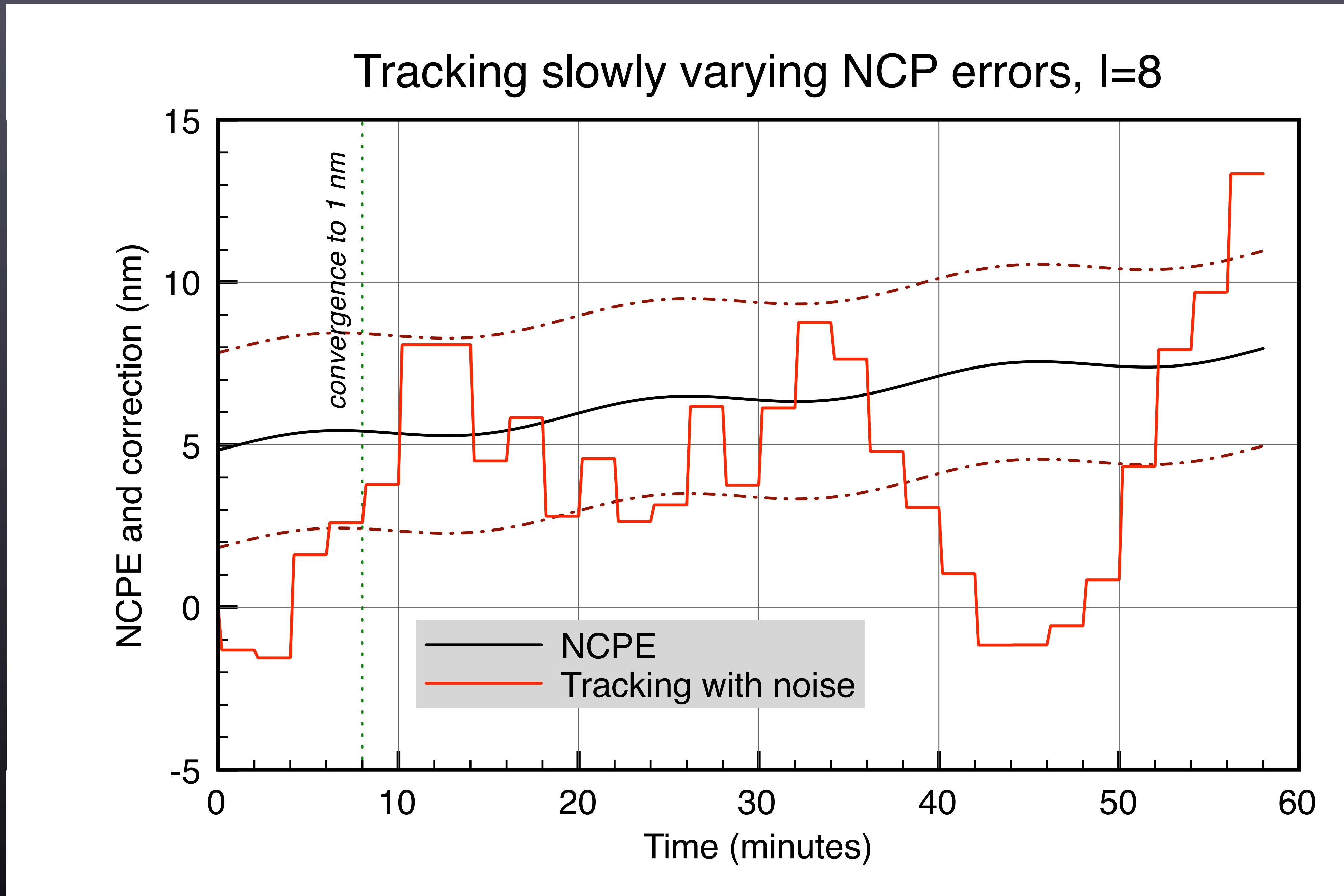


Tracking noise in steady state

GPI CDR results

IFS simulation step 1: detector images

- Part 1: light through the IFS
  - **setup up the observation: star [planet] parameters like magnitude, spectrum, observation length, field rotation, etc.**
  - **uses PSFs generated by AO simulation for both star and planet**
  - **several noise sources (detector noise, atmospheric transmission, sky background)**

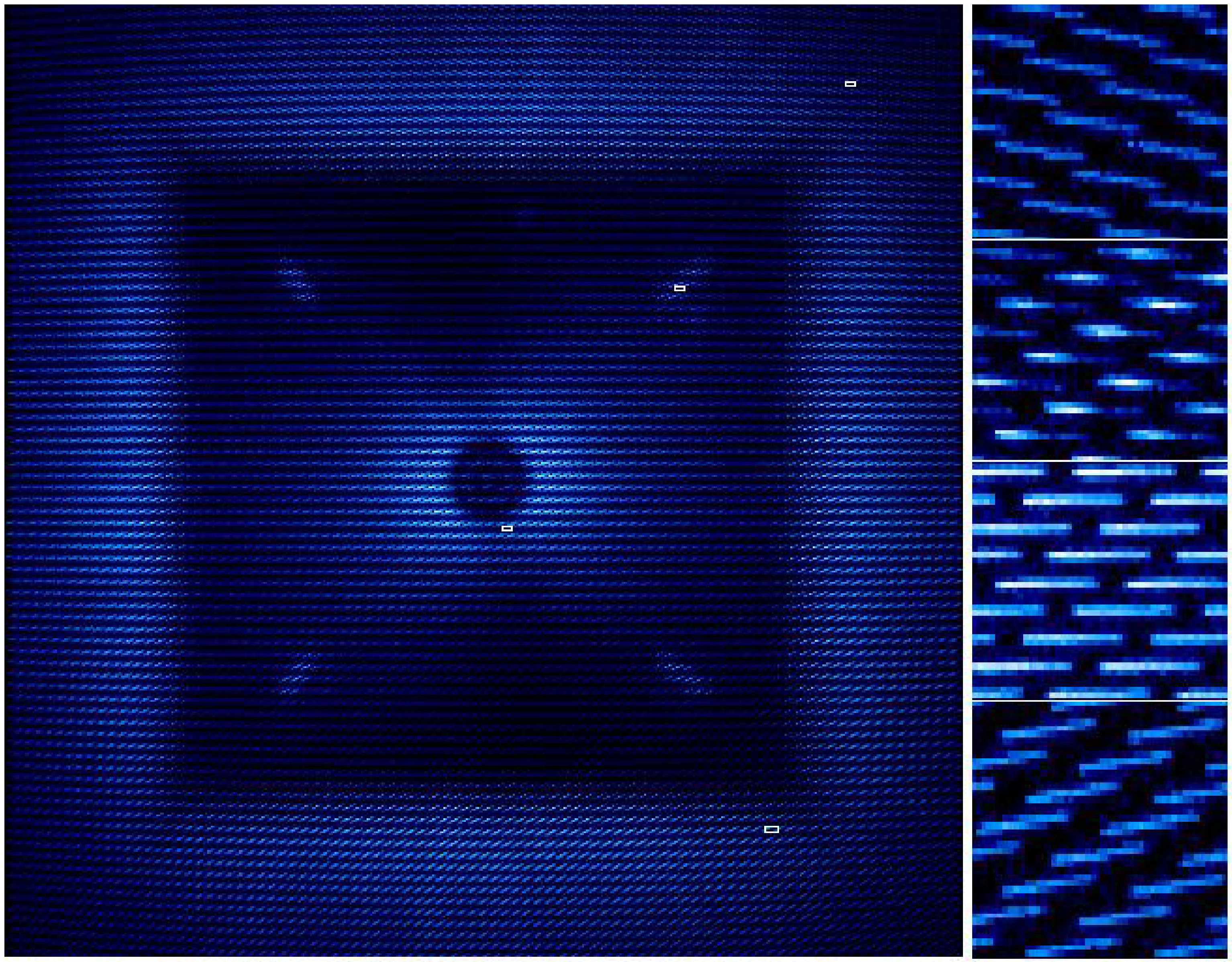
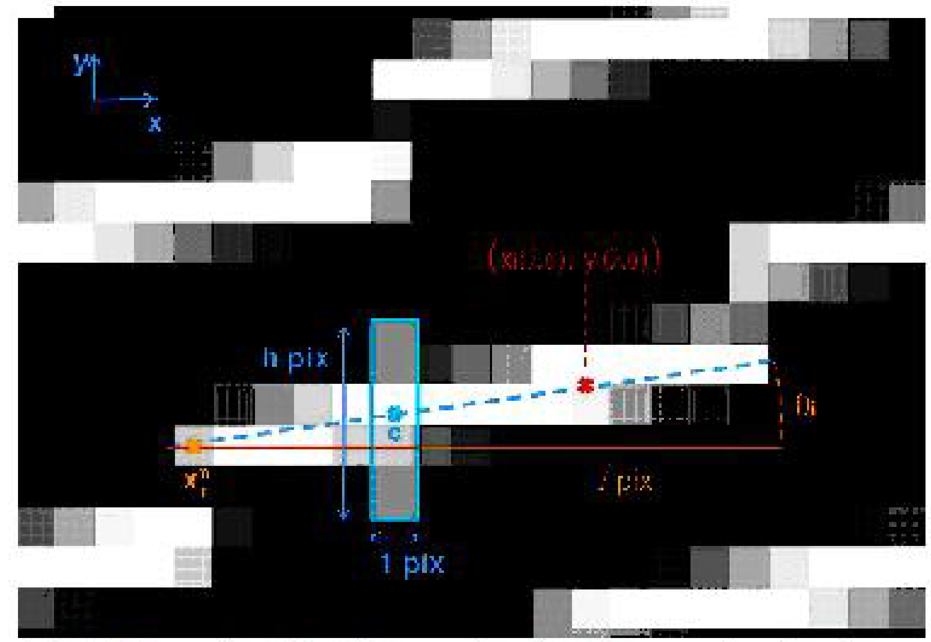
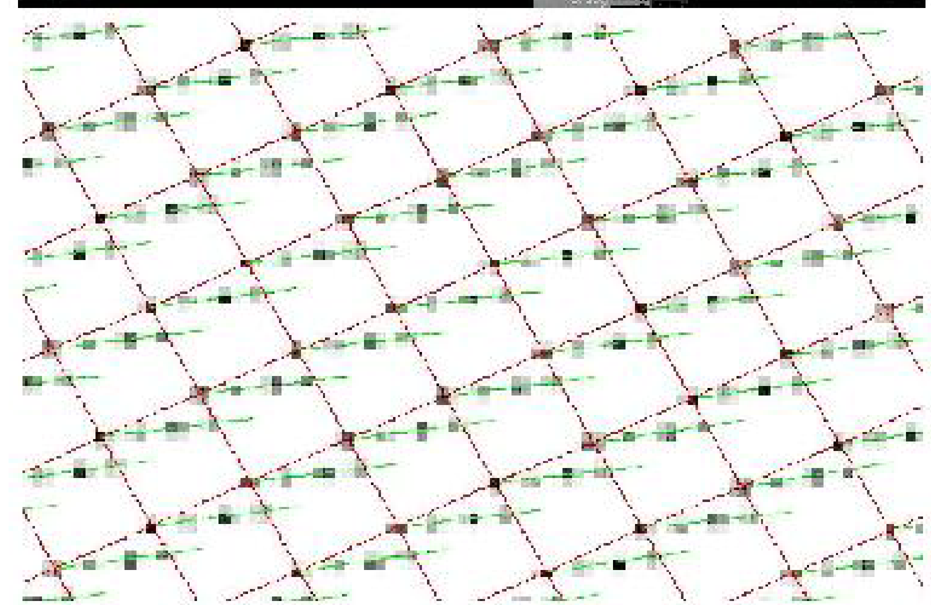


Figure from Maire, "Data reduction pipeline for the Gemini Planet Imager", SPIE 7735

IFS simulation step 2: build data cube

- Part 2: data pipeline to construct data cubes from IFS reads
  - **need to calibrate to get wavelength solution**
  - **from each IFS image, integrate over small regions; assign flux to a wavelength**
  - **interpolate onto common wavelength vector across all mini-spectra**





- This is non-trivial!

Figure from Maire, "Data reduction pipeline for the Gemini Planet Imager", SPIE 7735

Putting it all together

- For GPI performance, we have used a wide range of simulations and techniques to evaluate instrument performance
- For this workshop, I have linked several of these to make the data challenges.
- Good luck!
- Questions?